THE UNIVERSITY OF ALBERTA

THE PETROGRAPHIC AND ENGINEERING PROPERTIES OF FINE-GRAINED SEDIMENTARY ROCKS OF CENTRAL ALBERTA

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

SPRING, 1969

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled THE PETROGRAPHIC AND ENGINEERING PROPERTIES OF FINE-GRAINED, SEDIMENTARY ROCKS OF CENTRAL ALBERTA submitted by John Gary Locker in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

The fine-grained, near surface, sedimentary rocks of Late Cretaceous and Tertiary ages in central Alberta exemplify the transformation of a true "soil" to a true "rock". Corehole and outcrop samples of these rocks were studied to determine their petrographic and engineering properties, namely composition, texture, structure, plasticity and bulk properties such as bond strength, density, and peak and residual shear strengths. Linear and multiple regression analyses were performed to assess the relationships between measurable properties and other related geotechnical properties and geologic processes (diagenesis).

The Alberta rocks are mainly siltstones, with some highly plastic claystones and bentonites. The major components, quartz, feldspar, volcanic debris, montmorillonite, illite, organic matter, and carbonate cement, exhibit a variety of textures and structures which are illustrated by photomicrographs. In a general manner, the rocks indicate an increase in shear strength, density, and resistance to weathering across the province towards the Rocky Mountain Foothills in accordance with the influence of diagenetic processes.

ACKNOWLEDGEMENTS

It was the authors privledge to receive guidance from Dr. S. Thomson, Associate Professor, Department of Civil Engineering, University of Alberta, in the field of Soil Mechanics and Dr. G. B. Mellon, Head, Geology Division, Research Council of Alberta in the sister field of Geology. Both of these gentlemen provided the form of willing assistance for which the student will always be grateful.

Dr. J. B. Nuttal, Associate Professor, Department of Civil Engineering, University of Alberta made possible the application of the IBM 360 plotter.

Financial assistance for the student's program and research was provided by the National Research Council and the Research Council of Alberta.

The thin sections were ably cut by M. Baaske, Geology Division, Alberta Research Council.

To the many others who provided assistance, the author extends many thanks.

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GLOSSARY OF TERMS

argillaceous - containing or consisting of clay. The term is commonly combined with rock names to indicate the presence of clay.

authigenic - formed in place or generated on the spot. Applied to the constituents of rocks that originate with or later than the rock itself.

birefringence - the numerical difference between maximum and minimum indicies of refraction.

calcareous - consisting of or containing calcium carbonate

clastic - composed of broken fragments of minerals or rocks.

concordant bedding - An arrangement of bedded sedimentary rocks in which the layers are parallel and without angular junctions.

dessication - the drying out of sediments usually with shrinkage and strength increase.

detritus - any material worn or broken from rocks by mechanical means.

dip - the angle which a stratum makes with a horizontal plane, as measured in a plane normal to the strike.

eustatic - pertaining to world-wide changes of sea level that affect the entire ocean.

homocline - a group of strata which have a fairly regular amount of dip in the same general direction.

liquidity index - numerically equal to the natural water content minus the plastic limit divided by the plasticity index.

lithification - the transformation of liquid or loose materials into solid rock.

lithology - the physical character of a rock, generally as determined megascopically or with the aid of a low - power magnifier

metamorphism - process by which consolidated rocks are altered in composition, texture, or internal structure by conditions and forces not resulting simply from burial and weight of subsequently accumulated overburden. Pressure, heat and the introduction of new chemical substances are the principal causes and the resulting changes, which generally include the development of new minerals, are a thermodynamic response to a greatly altered environment.

milliequivalent - milliequivalent is the amount of a reagent required to combine or react with one thousandth of an atomic weight of hydrogen.

overconsolidation - stressed by loads greater than exist today.

residual strength - a minimum value of the strength components under drained conditions.

stratigraphy - that part of the descriptive geology of an area or district which pertains to the discrimination, character, thickness, sequence, age, and correlation of the rocks of the district.

strike - the direction of a line formed by the intersection of a bedding plane with a horizontal plane.

tectonic - pertaining to the rock structures and external forms resulting from the deformation of the earth's crust.

CHAPTER I

INTRODUCTION

The veneer of glacial deposits that covers the central Alberta Plains is underlain by a thick succession of relatively soft, gently dipping sedimentary strata of Late Cretaceous and Early Tertiary ages. These strata are of similar composition and origin, and, although "rocks" in a geologic sense, often exhibit a topography characterized by massive slumping where exposed along the valleys of postglacial streams and rivers (Hardy et al., 1962; Rennie, 1966; Hayley, 1968).

The instability of natural slopes developed in near-surface bedrock formations of central Alberta is well known to engineers and geologists alike, and a number of case histories documenting slumping phenomena in the eastern portion of this area have been reported (Sinclair et al., 1966; Painter, 1965). From these and other observations, it is apparent that the bedrock formations of central Alberta exhibit properties which suggest that they are neither true "rocks" nor "soils" in an engineering sense, but lie in a "grey zone" between these idealized end products. Thus, their behavior in engineering situations is difficult to predict on the basis of conventional theories and models or

by using conventional testing techniques, and it is difficult to determine in many cases whether the principles of soil or rock mechanics should be used in the analyses of such situations.

The questions then arise; what are the geotechnical properties of sedimentary materials in this grey zone between "soil" and "rock", and what are the relationships between these properties and the geologic attributes of such materials? It has been observed, for example, that the propensity for slope failure, i.e. slumping, along bedrock river valleys in central Alberta, appears to decrease in a westerly direction, towards the margin of the Rocky Mountain Foothills, in accordance with the apparent increase in induration or rock hardness in that direction. However, gross lithology and inferred depositional origins of the materials remain similar over this distance, and it may be postulated that post-depositional (diagenetic) processes have affected the bulk or mass engineering properties of these materials. Thus, it would be beneficial to determine those geological effects on variables that are associated with the transformation of soil to true rock, and to relate these variables to the behavior of the soft transitional materials of the "grey zone" in various engineering situations.

Scope of the Investigation

The investigation is essentially a pilot study of the engineering and geologic properties of the fine-grained, i.e. silty or clayey, Cretaceous-Tertiary strata of central Alberta. The program was set up with the following objectives in mind:

(1) to describe the basic attributes of these materials: namely, composition, texture, structure and derived mass properties such as density, plasticity, and shear strength;

(2) to determine the interrelationships among these properties;

(3) to assess the effects of diagenesis on the properties of these materials; for example, to assess the effects of compression, cementation and like phenomena on peak and residual strength.

To this end a series of outcrop and corehole samples was collected from near-surface bedrock formations of the central Alberta Plains, adjacent to a west-east line extending from within the Rocky Mountain Foothills to east of the City of Edmonton (Figure 1). Thus, samples of siltstone and claystone were collected from across the strike of the strata, in a direction that appears to coincide with a gradational change in the intensity of diagenetic effects, as exemplified by the change from hard, fractured rocks of the Foothills region to the soft, tectonically undisturbed materials of the

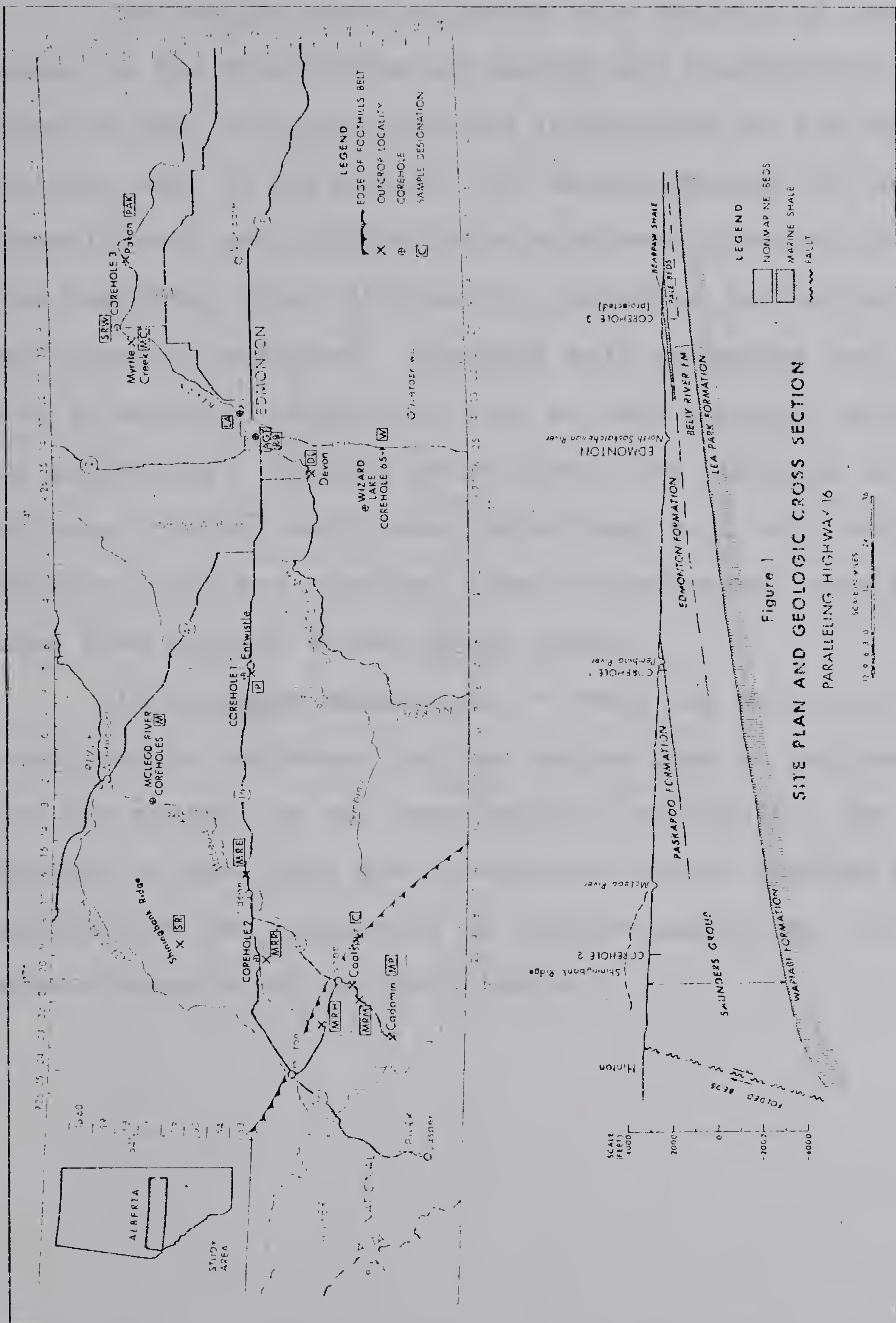


Figure 1

SITE PLAN AND GEOLOGIC CROSS SECTION

PARALLELING HIGHWAY 4 16

east-central Plains.

The samples were subjected to a variety of tests common to the disciplines of geology and engineering. Examination of thin sections provided information on the composition, texture, and, in particular, the microstructure of the samples. Compositional and textural data also were obtained from grain-size analyses, X-ray diffraction patterns, and conventional "wet" chemical analyses. Standard soil mechanics tests were used to evaluate properties such as bulk density, water content, and plasticity. Wet-dry cycle tests were employed to further evaluate inherent soft rock properties, e.g. bond strength. Effective peak and residual strength parameters were determined from drained direct shear tests.

All of these techniques or tests are well known to geologists or engineers but are seldom used in conjunction with one another on the same group of materials. The combination of data from such procedures should provide a clearer insight into the properties of complex materials, i.e. the bedrock deposits of central Alberta.

CHAPTER II

THEORETICAL BACKGROUND

Definition of Terms

Much of the research in soil mechanics has concentrated on the foundation engineer's chief problem soil - clay - which Terzaghi (1936) divided into stiff and soft clay on the basis of a liquidity index of less than 0.5 for stiff clay. Boulder clays, lacustrine clays which are overconsolidated by dessication, and heavily overconsolidated clays of Tertiary and older ages are all grouped as stiff clays (Morgenstern, 1967). However, the distinction between a soil (stiff clay) and a sedimentary rock (shale) is arbitrary in that there exist all gradations between the two materials. Terzaghi and Peck (1967) state:

> "The materials that constitute the earth's crust are rather arbitrarily divided by the civil engineer into two categories, soil and rock. Soil is a natural aggregate of mineral grains that can be separated by such gentle mechanical means as agitation in water. Rock, on the other hand, is a natural aggregate of minerals connected by strong and permanent cohesive forces. Since the terms "strong" and "permanent" are subject to different interpretations, the boundary between soil and rock is necessarily an arbitrary one. As a matter of fact there are many natural aggregates of mineral particles that are difficult to classify either as a soil or a rock."

From the point of view of simplicity, this definition is acceptable, but it does not give operational criteria for distinguishing between the two materials. For example, many compaction shales can be classified as rock by this definition (Philbrick, 1950) although their behavior is often like that of overconsolidated clays (Hardy et al., 1962). Therefore, although Terzaghi and Peck's concept can be used to differentiate between true "soil" and true "rock", i.e. for the end members of the system, materials with intermediate properties are left nameless. It is proposed here to call these transitional materials "soft rock" for want of a better term, which name implies that they are indeed sedimentary rocks from a geologist's viewpoint, although differing significantly from those indurated materials called "rock" by the civil engineer.

To clarify the terminology the following definitions are employed throughout the text :

Shale: a highly indurated, readily fissile rock composed of predominantly silt - and clay-sized particles.

Clay-shale: an indurated, readily fissile soft rock, which may revert to a clay of medium to high plasticity and assume the physical characteristics of a highly overconsolidated clay.

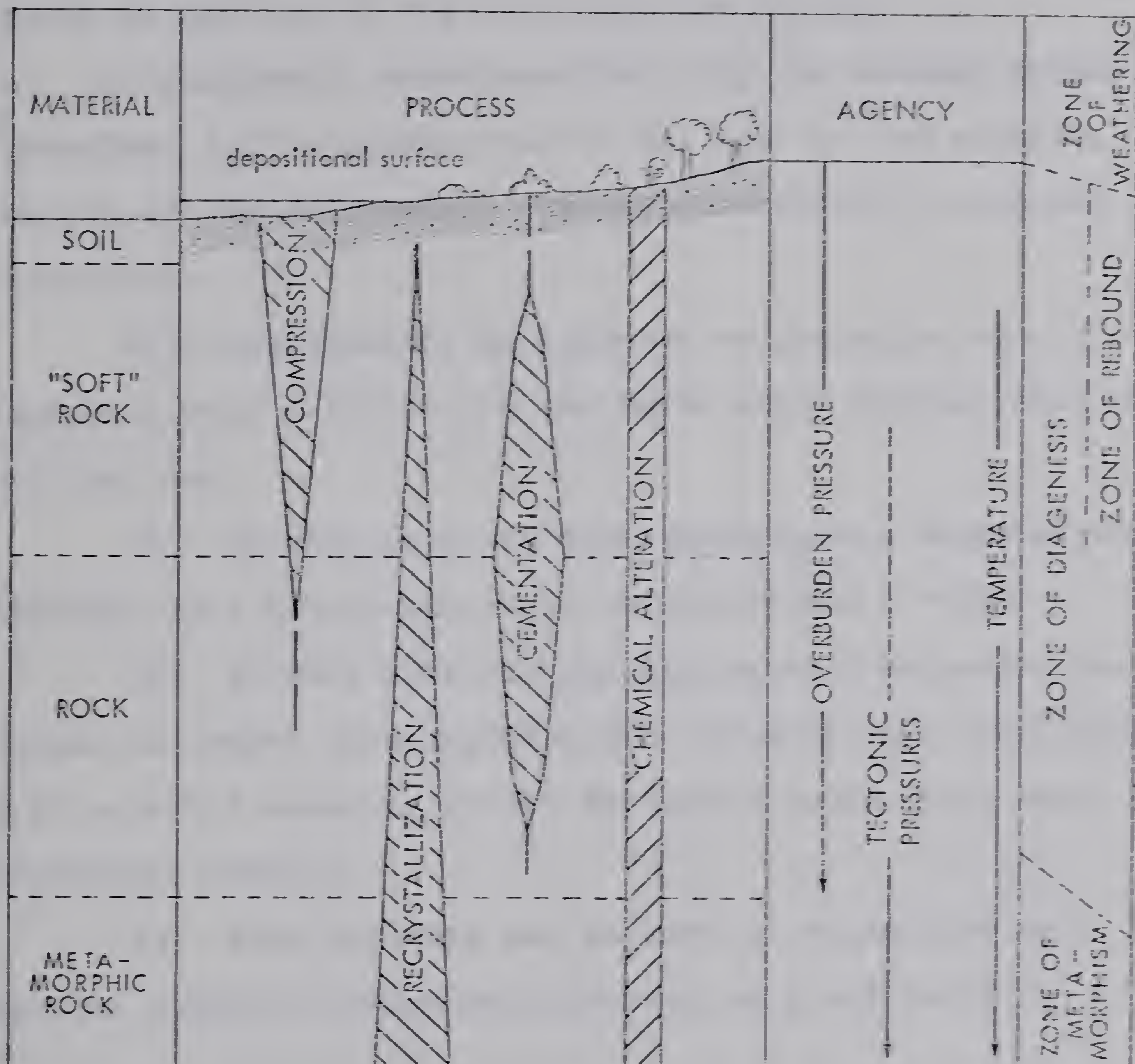
<u>Claystone:</u> a rock or soft rock (dependent upon the degree of induration) which is composed of predominantly clay-sized particles.

<u>Siltstone:</u> a rock or soft rock (dependent upon the degree of induration) which is composed of predominantly silt-sized particles.

Soil-Rock Transformation

The transformation of a sedimentary deposit from the state of a loose soil mass to that of a true rock involves a number of physical and chemical processes that can be grouped together under the general term "diagenesis" (Pettijohn, 1957). This transformation is illustrated schematically in Figure 2.

In nature, however, it is not necessary for the process to be carried to completion, i.e. a rock in the engineering sense of the term may not be formed. Natural conditions may be such that the required physical or chemical processes or the expenditure of energy are not conducive to complete transformation. Also, changes in the natural enviroment may reverse the direction of the diagenetic processes, and the mass will attempt to revert to the soil phase. Such a reversal may be caused by a reduction of overburden pressure due to the erosion of overlying material with resulting rebound. Hence, geologic age is not necessarily a measure of the degree of induration of sedimentary deposits. Indeed, soft rock may be found in formations as old as Cambrian (Mead, 1938).



SCHEMATIC REPRESENTATION OF SOIL-ROCK TRANSFORMATION TO ILLUSTRATE THE PROCESSES AND AGENTS OF DIAGENESIS

FIGURE 2

At any one point in the geologic time scale materials may be found at any stage indicated on the transformation diagram (Figure 2) and at this stage the material may be subjected to any one of the following conditions:
(a) the diagenetic transformation, (b) the rebound transformation, (c) a combination of (a) and (b) for example, rebound of the sedimentary mass with concomitant chemical alteration.

As a consequence, an engineer or geologist who is concerned with materials in the "grey zone" between soil and rock may ask:

(1) At what point in the system does a material cease behaving like a soil and begin behaving like a rock?

(2) At what point in the system are diagenetic processes no longer irreversible, i.e. at what point will rock-like material cease to revert to soil-like material when conditions permit?

(3) What criteria can be used to categorize the various stages of diagenesis between soil and rock?

Diagenesis

The complex processes which convert a newly deposited sediment into a rock are collectively referred to as diagenesis. This phenomena is almost synonomous with the term lithification (Pettijohn, 1957) but excludes those processes which occur at elevated temperatures and pressures, i.e.

metamorphic processes.

The exact nature of diagenesis is not clearly understood, although the major processes which are associated with this phenomena are outlined in Figure 2. They are:

(1) compression (or compaction as understood by the geologist);

(2) cementation;

(3) recrystallization;

(4) chemical alteration.

Compression

Compression is a physical process that results in a reduction of the bulk volume of the sediment. The degree of compression that a fine-grained sediment acquires is largely dependent upon: (a) gravitational pressure, (b) particle size, (c) clay mineral constituents and their adsorbed cations, and (d) type and concentration of electrolyte (Mead, 1964). The degree of compression in soft rocks as observed in deep boreholes in the Gulf Coast led Hedberg (1936) to recognize four stages of compression which grade into one another.

(1) mechanical rearrangement stage: This involves gravitational rearrangement of particles and expulsion of free water, that results in a decrease of porosity from an initial value of approximately 70 - 90 per cent to a value corresponding to the liquid limit.

(2) <u>dewatering stage:</u> This stage extends the compression process to the point where the clay particles begin to come into contact with each other. Free water is expelled from large cavities and adsorbed water is either expelled or redistributed, i.e. most adsorbed water is removed at grain-to-grain contacts.

(3) <u>mechanical deformation stage:</u> In this stage the porosities are about 30-35 per cent and the clay particles are in actual contact. The particles are close to a stable arrangement with respect to gravity, most adsorbed water at points of contact having been removed. Further compression involves bending and crushing of particles with some additional expulsion of adsorbed water. Previous to this stage, water supplied most of the binding force of the system, but with the contact of clay particles, chemical readjustment and recrystallization appear, and add to the rigidity of the system.

(4) <u>recrystallization:</u> In the fourth stage mechanical deformation decreases in significance as most components are in positions of permanent stability, and chemical alteration and recrystallization are dominant factors. Newly formed minerals fill the pores and further decrease porosity. Beyond this point, metamorphic processes associated with higher temperatures and pressures alter shales to slate.

Cementation

Cementation is the process associated with the deposition of minerals in the voids of a sediment. Cements common to fine-grained sediments are calcite, quartz, and iron compounds. Cementation may occur simultaneously with deposition (or after deposition) or after deposition and burial over a wide range of pressures and temperatures. Cementation tends to increase rigidity, strength, and density.

Where rocks are exposed to weathering phenomena, the reverse process, decementation, may occur depending upon the composition of the cementing agents and the intensity of the weathering processes.

Recrystallization

Recrystallization implies changes in sediment texture and structure without the addition of foreign mineral matter. Recrystallization may simply involve the development of larger crystals of the same basic mineral (e.g. development of coarse-grained rock salt from a fine-grained deposit), or the elements in the original minerals may regroup to form new compounds. The result is generally a stronger, denser material.

Chemical Alteration

These are the processes by which the mineral assemblages of a sedimentary deposit are altered to meet equilibrium con-

ditions during or after deposition. They usually involve the formation of new minerals by reaction between the solid constituents and pore fluids. The alteration of clay minerals is especially common, e.g. montmorillonite subject to potassium-bearing waters may alter to illite, and inherently unstable volcanic glass may alter to montmorillonite. A sediment may change colour when the ferric ion of iron compounds changes to the ferrous ion in a reducing environment.

The type of chemical alteration and its duration depend on the natural constituents of the deposit and the physico-chemical conditions under which the reactions take place.

Stress History and Recoverable Strain Energy

In many cases the degree of induration of rock or "soft-rock" materials can be attributed in part to the high overburden pressures under which the deposit was originally compressed. This situation is to be expected in nonfolded areas like the Alberta Plains, where the strata are nearly flat-lying and essentially undisturbed by the effects of horizontal compressive (tectonic) forces and associated high temperatures and chemical activities. Such compressive forces may well have exerted an influence on the Plains strata, but from a large scale structural point of view, the beds are undisturbed.

In such cases where the deposits have been subsequently unloaded by erosion of overburden, or by the melting back of the ice sheet in glaciated areas, the removal of overburden

pressures has resulted in the rebound of large areas underlain by soft rock formations. The loading and unloading conditions to which a soft rock has been subjected are responsible for the *in situ* stress condition at present.

The overburden pressures in the geologic history of a sedimentary deposit exert work to compress the deposit until a state of equilibrium is reached. It has been noted in the field and in the laboratory that part of the compression and hence part of the work or energy expended is of a recoverable nature. These concepts were clarified and expanded by Bjerrum in the Third Terzaghi Lecture (1967).

Most compressible deposits contain many flexible, plate-like particles, e.g. clay minerals or micas, which are distorted during loading. Upon removal of load these particles may attempt to regain their original configuration, thus, an increase in volume and a release of energy may occur. This energy is recoverable strain energy. The actual amount of volume increase or rebound is controlled by interparticle bonds which may prevent distorted particles from straightening to their original shape. Bjerrum referred to all bond types, e.g. those formed by recrystallization and cementation, collectively as diagenetic bonds. Hence, the magnitude of the load during compression and rebound, the composition of the deposit, and the strength of the interparticle bonds will influence the magnitude of the intrinsic stresses.

During compression of the deposit, the effective horizontal stresses increase with the vertical effective stresses in accordance with the shear resistance of the mass. When rebound takes place expansion will attempt to occur in the direction perpendicular to the plane of load removal. Surface erosion brings about greater changes in vertical stresses than in horizontal stresses. If the deposit is bonded there is a restriction of the strain. Destruction of the bonds by weathering allows strain to occur.

Thus in some clay deposits the strain is simultaneously recovered with a change of stress, whereas in others the strain does not take place until the bonds are destroyed. Ultimately lateral expansion of a slope may be sufficient to propagate the development of a failure surface. Bjerrum (1967) has classified over consolidated clays and clay-shales based on the strength of the bonds and the effect of weathering on the bonds. The classification system provides an indication of the potential danger inherent in these materials with respect to slope stability.

Shear Strength

As far back as the middle of the nineteenth century, Collins realized that the slopes of excavations in stiff clays and shales lost strength with time and ultimately weathered back to slopes comparable to nearby natural slopes which were considered stable with respect to a normal time scale. He attributed the loss of strength to progressive softening of the materials (Collins, 1846). The concepts of progressive softening and its effects on shear strength were expanded by Terzaghi (1936), Skempton (1948), and Cassel (1948), who postulated that fissured materials are susceptible to the infiltration of water which may soften the material adjacent to a fissure and decrease the strength of the mass. However, as progressive softening is a time-dependent feature, a cut may remain stable for long periods of time. Skempton (1948) presented a plot of drop in strength versus time in years which illustrates that the average strength of slopes in London Clay decreases to that of the soft clay in the fissures. He stated that the final strength along a slip surface is composed of the strength through both unsoftened and softened clay. These concepts are still considered in explanations of slope instability in highly overconsolidated, fissured clays and clay-shales.

Shear strength in the field maybe evaluated with the assumption that the overall factor of safety is unity at the

time of failure. Thus, if the slip geometry and enviromental conditions of failure are known, the average shear strength along a failure surface may be calculated. The mathematical manipulations involved in the solution of the mechanics of the problem are now readily handled by sophisticated methods, e.g. Morgenstern and Price, 1965. A field analysis, therefore, may provide an indication to the true average shear strength which exists on the slip surface at the time of failure.

In the laboratory the shear strength of stiff clay and sedimentary rock is evaluated chiefly by the means of the triaxial test, the direct shear test, and the unconfined compression test. The success of these testing procedures depends on the ability of the test to duplicate the conditions of failure in the field and on the ulilization of an undisturbed or intact sample which is representative of the mass under consideration.

Unfortunately, intact samples which are not necessarily representative of the fissured mass in the field are often used in testing. A strength test on such a sample provides a value of the peak strength of the material. However, the failure plane of a sliding surface in the field passes through both intact and fissured materials, so that some reduced value of strength should be applied in stability analysis.

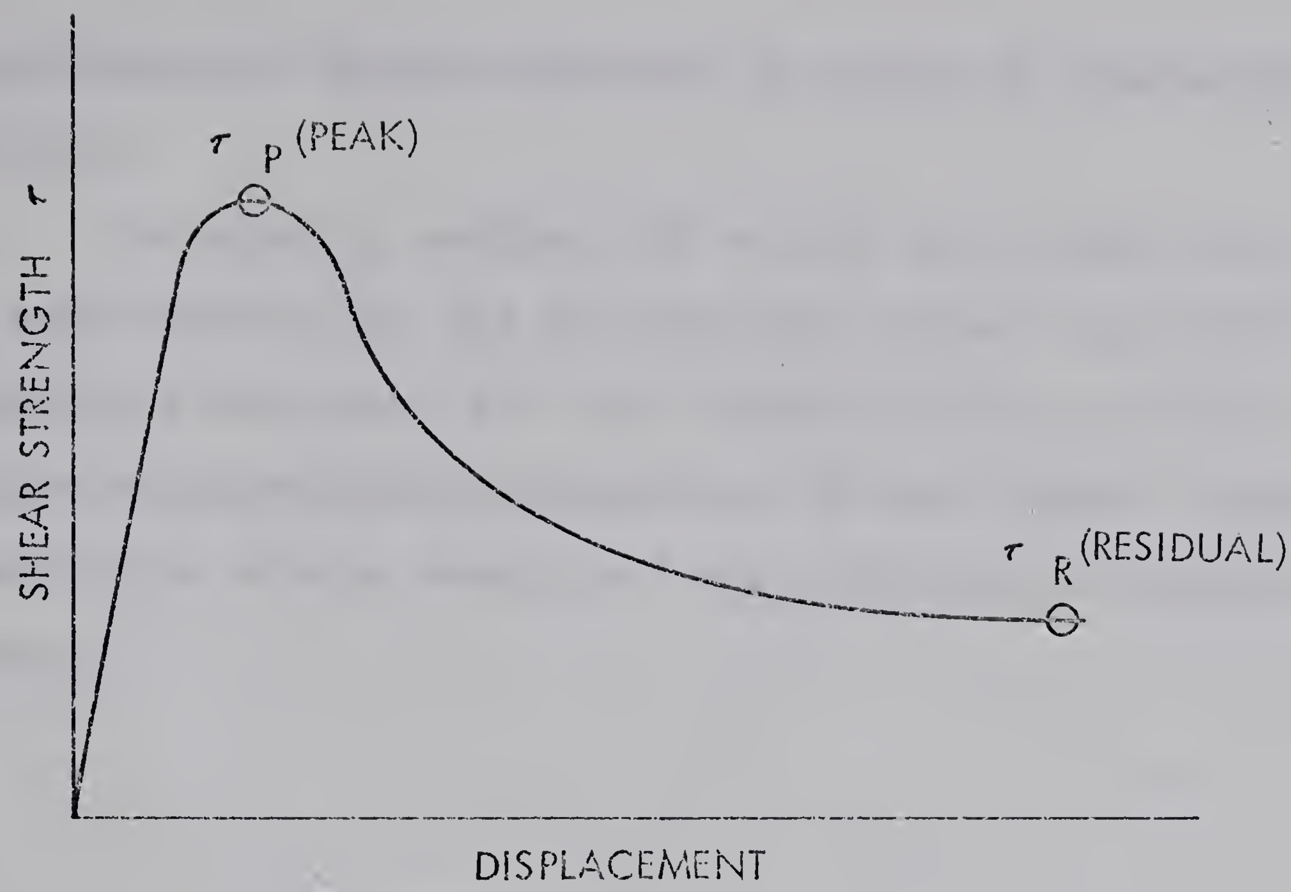
The reduced strength concept was clarified by Skempton (1964) when he emphasized the significance of residual

strength. Figure 3a illustrates the shear strength characteristics of an overconsolidated clay or soft rock in a drained test. With deformation, the material builds up a resistance until a peak value (τp) is reached; with continued displacement the strength decreases until a minimum value, (residual strength = τ_R is reached. If a series of similar tests under different normal loads is made, the peak and residual strength values can be plotted versus normal effective pressure to form two Mohr envelopes (Figure 3b). The residual strength of a material may represent the shear resistance that develops along fissures or at points in a mass which have been strained beyond peak resistance, as in a progressive failure situation.

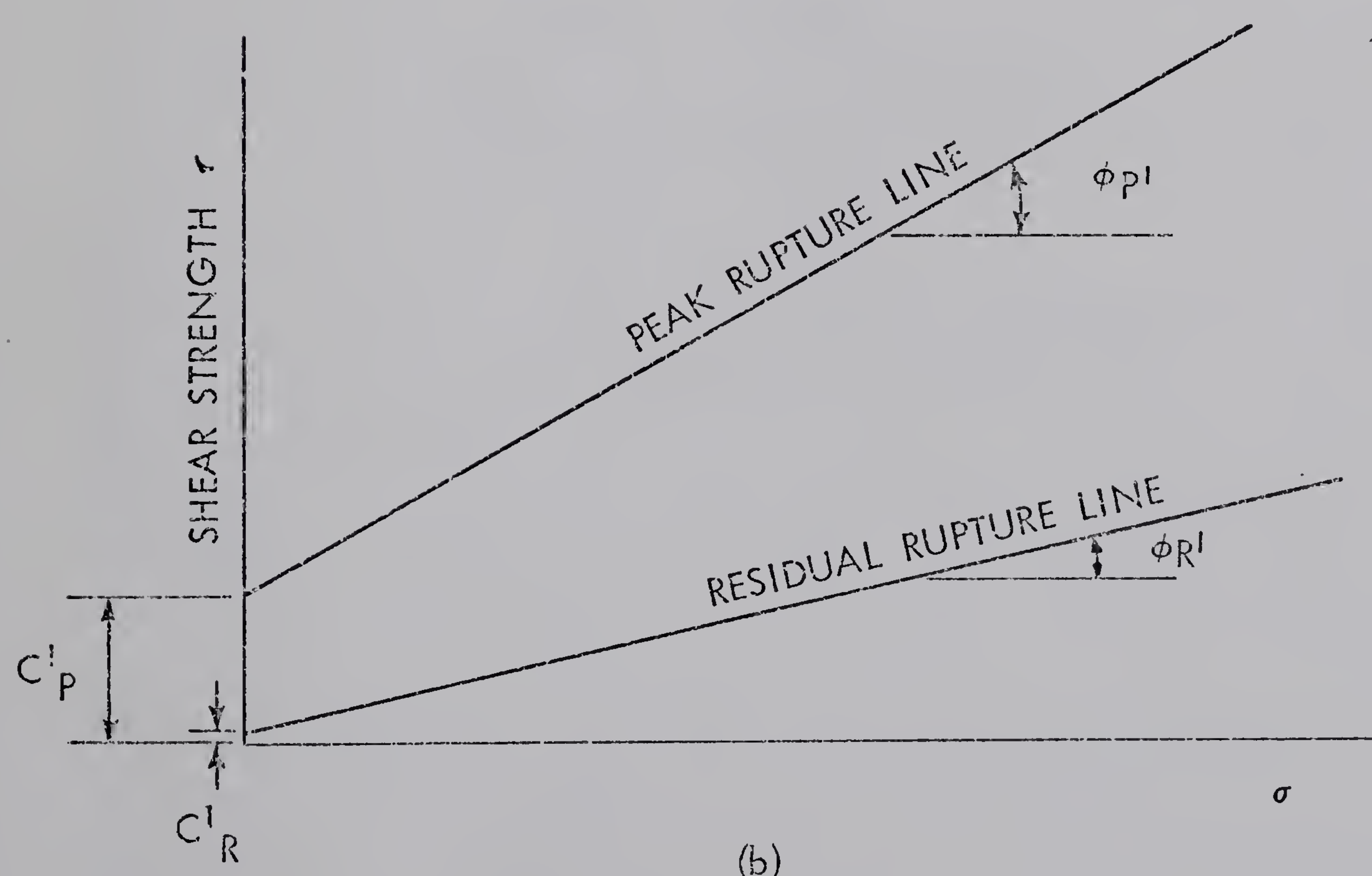
Slope Stability

In the Fourth Rankin Lecture, Skempton (1964) applied residual strength concepts to a number of recorded slope failures in fissured materials and introduced the term "residual factor". The residual factor, R, is the proportion of the total slip surface in the material along which the strength has fallen to the residual value and may vary in magnitude from 1 to 0. The stability of slopes in Alberta "clay shales" has been explained in terms of residual strength with R values near 1 (Sinclair, *et al.*, 1966).

Bjerrum (1967) applied the concepts of residual strength and recoverable strain energy to explain slope



(a)



(b)

EFFECTIVE SHEAR STRENGTH CHARACTERISTICS OF OVERCONSOLIDATED CLAY OR SOFT ROCK

FIGURE 3

instability of intact materials in terms of progressive failure.

In summary, analysis of a soft rock slope requires an appreciation of: (a) the concepts of peak and residual shearing resistance, (b) the residual factor, (c) the special engineering-geological properties of soft rocks, namely recoverable strain energy and the influence of diagenetic bonds.

CHAPTER III

GEOLOGY OF THE STUDY AREA

Selection and Location of Study Area

The study area lies in central Alberta between 53°00' and 54°00' North Latitude and between 111°00' and 117°30' West Longitude. As shown in Figure 1, it comprises an area of about 16,000 square miles, the largest part of which lies within the Interior Plains region, and a smaller portion in the southwest within the Rocky Mountains and Foothills.

The reasons for selecting this area are, firstly, accessibility: most of the sampling sites are on or adjacent to major highways and the remainder can be reached by municipal roads. Secondly, the geologic setting of the region is such that a relatively thick but lithologically homogeneous succession of strata can be sampled in an east-to-west direction, approximately across the strike of the rocks. This is the direction in which the apparent degree of induration increases, reaching a maximum in the folded and fractured true "rocks" of the Rocky Mountains and Foothills. Thirdly, the shallow bedrock formations of this region, especially in the east, present serious problems of slope stability, to which basic data on the geotechnical properties of the rocks may contribute

a better understanding.

Geologic Setting

The central Alberta Plains is an area of generally low relief underlain at shallow depths by a succession of predominantly nonmarine lenticular sandstones, shales, and coal beds of Late Cretaceous and Early Tertiary ages. These rocks, which exhibit varying degrees of compaction and cementation, form the "bedrock" of the region, being overlain in most areas by unconsolidated glacial and alluvial deposits of Pleistocene and Recent ages.

The bedrock structure of the Plains is that of a simple homocline, with the strata dipping gently westward at a few feet per mile (Fig. 1). Thus, successively younger strata outcrop at the bedrock surface in a westerly direction, to the point where they abut against the margin of the Rocky Mountain Foothills, where strata ranging in age from Paleozoic to Tertiary are folded and faulted into a series of northwesterly-trending thrust sheets arranged in such a way that successively older strata are exposed in a westerly direction. The geology of the folded Foothills and adjacent Rocky Mountains region is complex, and does not warrant further discussion here.

The eastern portion of this area is one of generally low relief, with a gradual rise in regional elevation from east to west. Topography is more irregular in the western

part of the area, where concordant, flat-topped hilly areas and isolated ridges gradually rise in places to more than one thousand feet above the surrounding level of the Plains (e.g. Shiningbank Ridge). These areas, composed mainly of bedrock, constitute the remnants of a dissected plateau, merging to the west with the more pronounced valley and ridge topography of the folded Foothills region.

The land surface was modified to some extent by widespread glaciation during Late Pleistocene time, with the superimposition of local depositional and erosional topographic features upon the preglacial bedrock surface. Such features include.

(1) topographic highs due to deposition of glacial and proglacial moraine, outwash, and aeolian deposits;

(2) filling-in of preglacial stream valleys by glacial deposits;

(3) topographic lows mainly due to scouring of bedrock by meltwater channels.

Local relief also is provided by the valleys of two major river systems, the Athabasca and North Saskatchewan, which drain the western and eastern parts of the area respectively. These rivers and such major tributaries as the McLeod and the Pembina are entrenched in narrow, steep-sided valleys 200 to 300 feet below the general land surface in places, although elsewhere, where they follow or cut across wide preglacial stream valleys, the local relief generally is much less.

Stratigraphy and Lithology

The shallow bedrock formations of the study area constitute a succession of lenticular detrital strata of predominantly nonmarine origin. The beds, which range in age, from Late Cretaceous to Early Tertiary, are divisible into several rock units indicated on Figure 1.

Belly River Formation ("Pale beds[1]")

Beds assigned to the upper part of the Belly River Formation ("Pale beds") are the oldest of the bedrock formations exposed in that part of the Alberta Plains covered by the study-area. They underlie the eastern part of the region, cropping out along the North Saskatchewan River and its tributaries downstream from Edmonton.

The unit is composed of complexly interbedded pale grey, bentonitic sandstone, laminated silty and sandy shale, and medium to dark grey, carbonaceous claystone. Thin beds of dark brown-weathering sideritic ironstone and thin coal seams also are present. The beds, deposited in a coastal plain or deltaic environment, closely resemble the highly bentonitic rocks of the overlying Edmonton Formation in the field, although they appear to be sandier in overall aspect.

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[1] Sometimes now referred to as the Oldman Formation.

Bearpaw Formation

The Bearpaw Formation underlies a large area in southern and east-central Alberta, where it consists primarily of dark grey marine shale, glauconitic sandstone, and thin bentonite beds. It thins to the north and west by interfingering with deltaic sediments in the lower and middle parts of the Edmonton Formation, so that in east-central Alberta the Bearpaw is present only as a thin shale unit 10 to 25 feet thick separating the "Pale beds" from the overlying Edmonton Formation (Allan, 1917). In the western part of the study-area, the unit looses its lithologic identity entirely, and stratigraphers commonly do not distinguish between the Belly River and Edmonton Formation in this region (Figure 1).

Edmonton Formation

The Edmonton Formation of latest Cretaceous age crops out over a large area in east-central Alberta. In the study-area it forms the near-surface bedrock for a distance of about 70 miles perpendicular to the strike of the beds, extending parallel to Highway 16 from about 30 miles east of Edmonton to the Pembina River at Entwistle (Fig. 1). The eastern or lower boundary of the formation is defined by the contact with the underlying Bearpaw Shale; the western or upper boundary is marked by the contact with the overlying Paskapoo Formation. The formation is about 1500 feet thick near its western outcrop margin, thickening in the subsurface

to the west towards the edge of the Foothills.

The Edmonton Formation consists mainly of soft-weathering, fine-grained clastic sediments deposited in fresh - to brackish - water enviroments. The predominant lithologies are pale-weathering, fine-grained, bentonitic sandstone and siltstone interbedded with and grading vertically and laterally into grey to brown, bentonitic, silty claystone. Coal seams and bentonite beds of variable thickness are present throughout the formation, together with thin dark brown-weathering beds of sideritic sandstone and claystone. The beds are lenticular and difficult to trace even locally owing to the lateral gradation of one lithology into another over short distances.

The mineral composition of the Edmonton Formation beds is characterized by the high proportion of volcanic detritus in the sand and silt fractions: angular quartz, feldspars and finely crystalline volcanic rock fragments. Biotite mica and comminuted carbonaceous matter are common, and where they are abundant these platy constituents help to enhance the fissility of the rocks. The dominant clay-size constituent is montmorillonite, present commonly as a sandstone cement and also as the main component of the claystones. Montmorillonite commonly is associated with the alteration of volcanic glass, and the presence of altered shard-like outlines in thin sections of some of the predominantly bentonitic rocks suggests a post-depositional origin for

this material in the Edmonton Formation rocks.

Detailed classification of the rock types of the Edmonton Formation in the field is made difficult by the gradational nature of lithologic contacts and by the finely laminated nature of the siltstones and claystones. However, the following gross lithologies can be recognized in outcrops and cored sections on the basis of general compositional-textural features and derived properties, such as color.

(1) sandstone: generally soft, grey-to white-weathering and fine-grained. Some hard, calcareous-cemented bands stand out as flattened or spherical nodules that are more resistant to erosion than the more common bentonitic sandstones.

(2) clay-shale and siltstone: these lithologies constitute a gradational series of rock types difficult to categorize in the field. Many so-called "shales", for example, contain a high proportion of silt-size quartz, feldspars, and other detritus, grading at one end of the scale into siltstone and at the other into bentonite. Also, most such rocks do not exhibit fissility and thus are mudstone or claystone rather than "shale". The following rock types are recognizable among this group:

(a) grey shale and siltstone: light to dark grey, laminated to structureless rocks with a highly variable silt content;

(b) carbonaceous shale: brown to dark grey, soft to hard, generally silty-rocks with variable amounts

of carbonaceous material and fossil plant fragments in thin layers or partings; grades with the addition of organic material into impure coal beds;

(c) bentonitic shale: yellowish-brown to bluish-grey soft, "soapy" rock with minor silt content; may be laminated or structureless;

(d) bentonite: bluish-green to pale cream, very soft to mushy material composed mainly of montmorillonite.

(3) ironstone: hard, dark brown-to orange-weathering, fine-grained, irregularly bedded rock composed mainly of finely crystalline siderite, clay minerals, and variable amounts of sand-and silt-size detritus.

Paskapoo Formation and Saunders Group

The western part of the study-area, between the Pembina River on Highway 16 and the eastern edge of the folded Foothills belt, is underlain by a thick succession of gently-dipping sandstones and shales, similar in gross lithology to the beds of the underlying Edmonton Formation. These strata are mapped as Paskapoo Formation in the eastern part of this region and as the Saunders Group to the west (Map 1002A, Geol. Surv. Canada, 1951), although for practical purposes there is no obvious distinction between the two units. Contrary to Rutherford's original interpretation (1928), deep drilling in the area indicates that both the

Paskapoo and Saunders beds dip gently to the west, with successively younger strata being exposed adjacent to Highway 16 towards the Foothills (Fig. 1), (G. B. Mellon, pers. comm.).

The Paskapoo and Saunders beds consist in outcrop of relatively soft-weathering, lenticular sandstone, siltstone, and claystone of nonmarine origin. Thin coal beds are present and lenses of quartzite pebbles are found as the Foothills are approached.

Sandstones are found as fine-to medium-grained, relatively homogeneous units ranging in thickness from a few inches to 100 feet. Such beds are relatively soft but appear less bentonitic or clayey than the sandstones of the underlying Edmonton Formation, although hard, resistant, calcareous lenses are commonly present. The sandstones are composed of quartz, chert, feldspars, and finely crystalline rock fragments, containing on the average less volcanic detritus than the Edmonton Formation sandstones to the east (G. B. Mellon, pers. comm.).

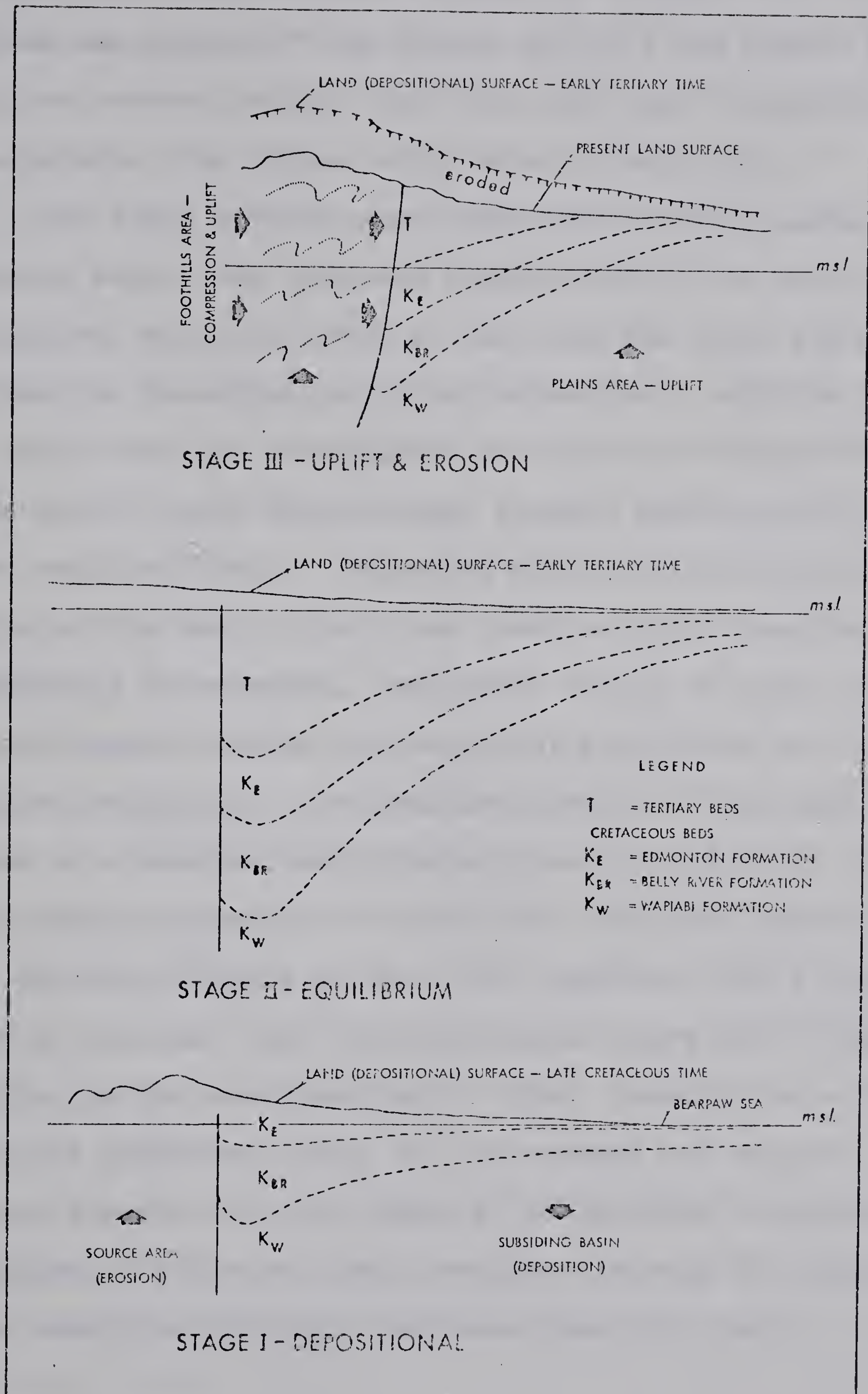
The siltstone and claystone beds are thinner than the associated "massive" sandstones, consisting of medium to dark grey or greenish-grey rocks with thin sandy interbeds. Carbonaceous shales are present, grading in places into thin impure coal beds. The less silty claystones are soft, blocky fracturing rocks with little inherent fissility.

The similarity of gross lithologies throughout the succession, the lenticular nature of the beds, and the lack of outcrops makes subdivision and correlation of the post-Edmonton succession (of the western Plains) difficult.

Historical Geology

Late Cretaceous-Tertiary bedrock formations of central Alberta form the upper part of a thick succession of clastic rocks ranging in age from Jurassic to Paleocene, which was deposited in a subsiding basin flanking highlands situated to the south and west of the present Rocky Mountains. These "highlands", the site of erosion rather than deposition throughout most of the period under consideration, provided the detritus (including much volcanic material) which accumulated in the basin to the east, the amounts and composition varying from time to time, depending on such factors as the composition of the source rocks, the rate of uplift, topography, and climate. Thus, each gross lithologic unit or "formation" in the basin records an episode in a series of tectonic uplifts in the source region and concomitant down-warps in the marginal basin spread over a period of more than 100 million years (Alberta Soc. Pet. Geol., 1964)

Figure 4 shows a series of schematic cross sections across the Alberta basin and hypothetical source area which record the major episodes of deposition and erosion from Late Cretaceous to recent times (G. B. Mellon, pers. comm.).



SCHEMATIC REPRESENTATION OF STAGES OF GEOLOGIC HISTORY OF CENTRAL ALBERTA

FIGURE 4

Although the vertical scale is greatly exaggerated, and the position and extent of the source area and the degree to which the western part of the basin has been forshortened are uncertain, the scheme holds true in principle.

The first section shows the relationships among the subsiding basin, the highland source area to the west, and the inferred mean sea level at the time the lower part of the Edmonton Formation was being deposited. Detritus from the source area was transported by eastward-flowing streams to the basin over a depositional surface which sloped gently to the south and east. Sediments deposited in the western portion of the basin, above sea level at that time, consisted of complexly interbedded, lenticular bodies of sand, silt, clay and organic matter now mapped by geologists as the "Edmonton Formation". The eastern portion of the basin was covered by a shallow sea in which fine-grained silty clays of the Bearpaw Formation accumulated. With the passing of time, eustatic changes in sea level combined with a steady influx of sediment from the west caused migration of the shoreline to the south and east. Thus, towards the end of Cretaceous (Edmonton) time, all of central and most of southern Alberta were the locus of continental (nonmarine) deposition, a situation that prevailed through the deposition of the overlying Tertiary (Paskapoo-Saunders) beds.

The net result of these processes was to create a wedge-shaped blanket of lenticular, complexly interbedded, clastic and organic deposits, that, owing to the greater rate of subsidence (and hence, deposition) in the west, thickens in that direction. Except for the marine Bearpaw deposits, the various rock units were deposited by a series of aggrading streams flowing eastward across a gently sloping subaerial plain. Periodically, parts of the relatively flat depositional surface were sufficiently low and the supply of detritus sufficiently restricted to permit the accumulation of masses of organic matter, subsequently transformed into coal beds now associated with the Edmonton and younger formations.

Towards the end of early Tertiary (Paleocene) time, events took place which transformed the Alberta basin from an area of subsidence and deposition into an area of uplift and erosion, processes which are still continuing. Figure 4 (Stage 2) shows the schematic configuration of the source area and basin just prior to mountain-building movements that brought about this transformation at the end of Paleocene time.

These mountain-building movements ("Laramide Orogeny" of geologists) are associated usually with compression and uplift of the western part of the basin, where the highly folded and faulted strata of the Rocky Mountains and Foothills are now situated. The duration of this process is uncertain,

but its inception appears to have coincided with regional uplift of the eastern part of the basin as well as the folded western part, and the beginning of the long period of erosion that has persisted to the present day. For example, Rutherford (1928) estimates that approximately 2000 feet of strata have been removed from the study area during Tertiary time, if it is assumed that there has been no appreciable denudation of remnant plateaus such as Shiningbank Ridge. Consequently, as indicated in Figure 4 (Stage 3, the outcrop margins of various formational units have been stripped back in a westerly direction, with the younger Tertiary beds being preserved only in the western Plains and adjacent Foothills.

The prolonged period of erosion that took place in Tertiary time is largely responsible for the broad topographic outlines of the Alberta Plains as observed today. Locally, however, the late Tertiary landscape has been modified by Pleistocene glaciation, which has left a veneer of surficial deposits from a few inches to several hundred feet thick over most of the region. The net effect of glaciation on topography is variable. In places, hummocky moraine deposits have enhanced the local relief by two or three hundred feet, or glacial meltwaters have cut steep-sided stream trenches into underlying bedrock. Elsewhere, preglacial valleys and other local depressions have been filled in by glacial deposits, resulting in a reduction in local relief.

Subsequent to the retreat of Pleistocene glaciers about ten thousand years ago, renewed erosion by larger streams and rivers has in places cut steep-sided valleys through glacial deposits and bedrock to depths of 200 to 300 feet below the general Plains level. Thus, Pleistocene glaciation can be considered as a relatively minor interruption of the processes of uplift and erosion of the Alberta Plains that have continued since early Tertiary time.

CHAPTER IV

SAMPLING AND ANALYTICAL PROCEDURES

Description of Sampling Sites

A total of 74 samples were collected for analysis from 11 outcrop and 8 subsurface localities, Figure 1, the descriptions of which are summarized in Table I. The sampling sites are arranged in an east-west direction, oblique to the northwesterly-trending strike of the strata, having been chosen with a view to accessibility, and to obtaining representative material from major lithologic units of the Plains and Foothills regions.

All but one of the outcrop sites (SR), sampled during the summer of 1967, were selected at localities readily accessible to major highways or forestry trunk roads. The majority are along post-glacial river or stream valleys, but some material from highway and railway cuts is included.

Sections of some river valley banks and a highway cut sampled south and west of Edmonton are illustrated in Figure 5. These slopes are in the order of 45 degrees and appear to be stable at heights up to 250 feet. East of the city of Edmonton, outcrops are scarce and confined mainly to the valley of the North Saskatchewan River and the mouths of tributary creeks

DESCRIPTION OF (ABOVE) OUTCROP SITES AND (BELOW) COREHOLE SITES IN CENTRAL ALBERTA

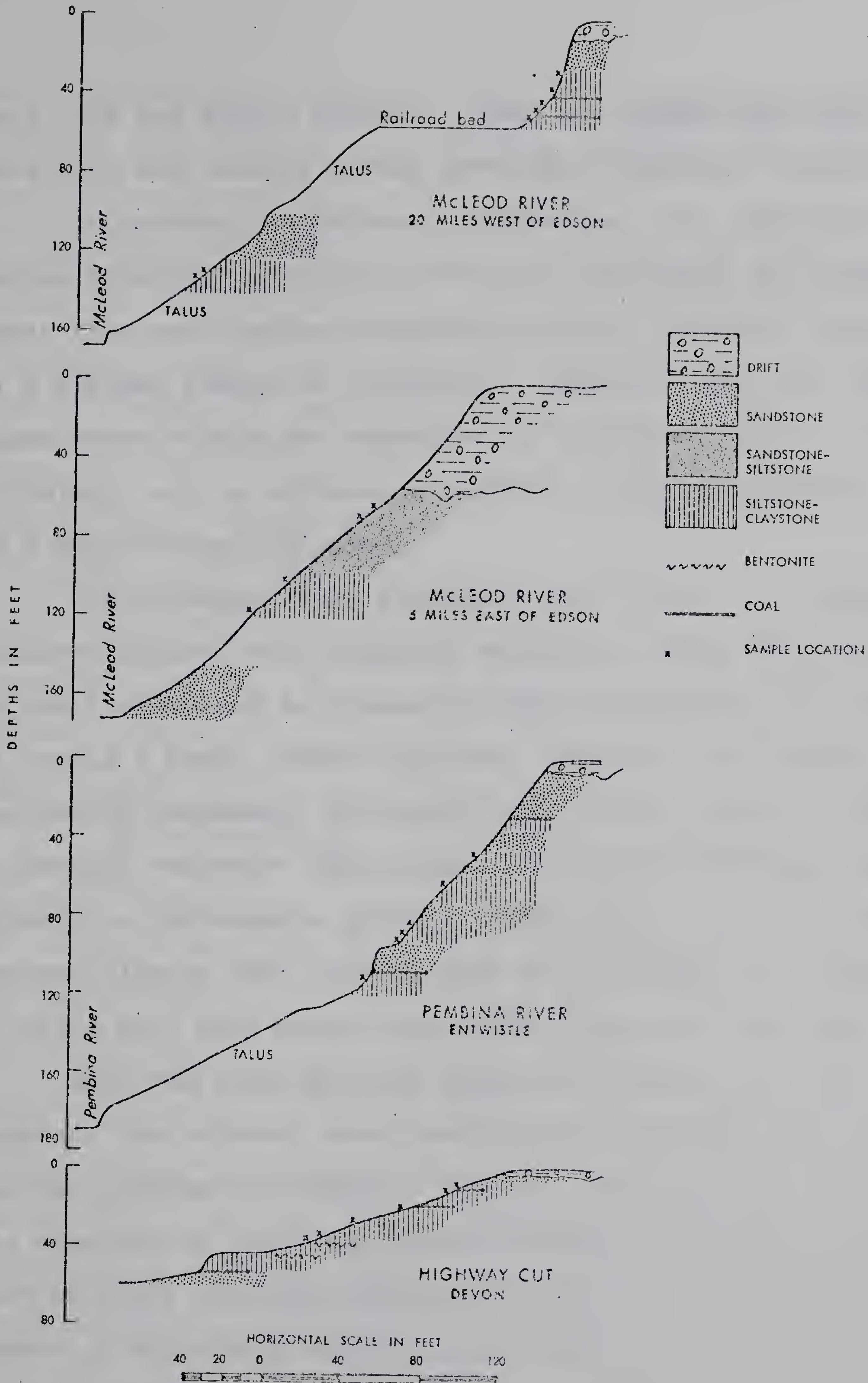
TABLE I

Locality	Sample Designation	Location	Formation or Group	Number of Samples	Description
McLeod R[1], Hinton-Robb Forestry Road	MRH	Tp. 50, R.23, W.5M[2]	Saunders Gr.	5	River Bank, dip of beds - 25 °
Cadomin	MP	Sec. 5, Tp. 47, R.23, W.5M	Mountain Park Fm.	3	Rwy.[5] Cut, dip of beds - 45° "real" rock
McLeod R, Mercoal	MRM	Sec. 14, Tp. 48, R.22, W.5M	Saunders Gr.	4	Rwy.[6] Cut, dip of beds - 70° - 80°
Coalspur	C	Sec. 29, Tp. 48, R.21, W.5M	Saunders Gr.	2	Rwy. Cut, dip of beds - 40°
McLeod R, Marlboro	MRR	Sec. 32, Tp. 52, R.20, W.5M	Saunders Gr.	7	River Bank and Rwy. Cut
Shiningbank Ridge	SR	Sec. 30, Tp. 56, R.19, W.5M	Saunders Gr.	1	Small Gully Bank
McLeod R., Edson	MRE	Sec. 20, Tp. 53, R.16, W.5M	Saunders Gr.	4	River Bank
Pembina R., Entwistle	P	Sec. 29, Tp. 53, R.7, W.5M	Lowermost Paskapoo Fm. and Uppermost Edmonton Fm.	6	River Bank, thick beds of calcareous sandstone
Devon	DL	Sec. 3, Tp. 51, R.26, W.4M	Edmonton Fm.	6	Hwy. Cut, Height 55', Slope
Myrtle Creek	MC	Sec. 23, Tp. 58, R.20, W.4M	Belly River Fm.	2	River Bank, Height 35', Slope 20°
Egg Creek, Pakan Ferry	PAK	Sec. 12, Tp. 58, R.17, W.4M	Belly River Fm.	2	River Bank, Height 70', Slope 20°

1. R. - River
2. Sec. - Section, Tp. - Township, R - Range, W.5M - West of 5th Meridian
4. Fm. - Formation
5. Rwy. - Railway
6. Hwy. - Highway

Corehole Locality	Sample Designation	Location	Formation or Group	Number of Samples	Description
McLeod R[1], Marlboro	MRR	Sec.32, Tp 52, R.20, W.5M	Saunders Gr.	2 - D/S[2] 2 - classification	85' deep, 150' North and 700' west of outcrop "MRR"
*[3] McLeod R, 20 mi. W. of Whitecourt	M	Sec.33, Tp 57, R.13, W.5M	Lowermost Paskapoo and Uppermost Edmonton Fm.	6 - classification	airdried samples selected from series of coreholes across river valley
Pembina R, Entwistle	P	Sec.29, Tp 53, R.7, W.5M	Lowermost Paskapoo and Uppermost Edmonton Fm.	2 - D/S 5 - classification	120' deep, 200' west of outcrop "P"
*Wizard Lake	W	Sec.8, Tp 48, R.27, W.4M	Lowermost Paskapoo and Uppermost Edmonton Fm.	9 - classification	airdried samples from 500 ft. corehole R.C.A.[4] - 1967
*Edmonton	AGT	Sec.4, Tp 53 R.24, W.4M	Edmonton Fm.	4 - classification	samples at natural water content, selected from series of holes at building site
*N. Saskatchewan R, University	RB	Sec.32, Tp 52, R.24, W.4M	Edmonton Fm.	3 - D/S 3 - classification	from series of holes, 116' deep, Dept. of Civil Eng. River Bank Stability Report, 1968
*N. Saskatchewan.R, Lesueur Slide	LA	Sec.27, Tp 53, R.23, W.4M	Edmonton Fm.	1 - D/S	110' deep (Pennell, 1969)
N. Saskatchewan R, Waskatenau	SRW	Sec.32, Tp 58, R.19, W.4M	Belly River Fm.	2 - D/S 2 - classification	60' deep

1. Abbreviations as above
2. D/S - Direct Shear
3. *denotes pre-study corehole
4. R.C.A. - Research Council of Alberta



SECTIONS OF TYPICAL OUTCROP SITES IN CENTRAL ALBERTA

FIGURE 5

(e.g. Egg and Myrtle Creeks). They are seldom more than 50 feet high and usually partly covered by talus and vegetation.

In outcrop, sandstones, siltstones, and claystones are seldom separated from one another by boundaries but rather grade into one another, seemingly without regulated order, by a gradual change in lithology. However, there are some cases where strata are separated by a discrete change in lithology, e.g. a calcareous sandstone bed resting directly on a well-defined claystone.

The siltstones and claystones are present as highly-fissured masses, with segments varying in shape from blocks to small slabs and in dimension from a fraction of an inch to nearly a foot. These segments, which have been derived by weathering phenomena, are acted upon by the forces of erosion to develop extensive talus slopes of fragmented rock, particularly in the western portion of the study area. In east-central Alberta the fissured rock has reverted to a clayey or silty soil mass which mantles the slope and forms the talus.

Only the finer-grained clayey and silty beds were sampled; the thicker, more homogeneous sandstone beds present special problems of analysis and were excluded from the study. The sampling of outcrops involved removing the outermost 1 to 2 feet of highly fissured material and selecting representative pieces of claystone, siltstone, and bentonite from different beds, as distinguished by colour, grain size, and degree of induration. Those samples which were to be thin-sectioned were

treated with extreme care and were marked to indicate the direction of bedding. All samples were sealed in plastic bags to prevent moisture loss.

Outcrop material was supplemented by samples selected from five coreholes drilled previous to or concurrently with the study (McLeod River, Wizard Lake, Lesueur slide, AGT building site, River Bank stability study; Figure 1) and from three coreholes drilled specifically for the purposes of the investigation (coreholes 1, 2 and 3; Figure 1). The number of coreholes that could be drilled specifically for this study was limited by economics; in addition, time and equipment placed restrictions on the number of direct shear tests that could be performed effectively. Thus, it was imperative that the coreholes be selected to provide materials representative of the maximum variations in soft rock characteristics across central Alberta.

The locations of the coreholes drilled to provide samples for shear tests were determined from the results of density tests performed on outcrop samples. These tests indicated a relatively systematic variation in geotechnical properties of the different rock units across the study area and thus, the drillholes were spaced at approximately equal increments of distance across the Plains portion of the study area at roughly sixty mile intervals in a west-to-east direction (Figure 1). The coreholes also are situated close to sample

outcrop sections, so that drilling operations were facilitated by a general knowledge of the lithologic profile.

Drilling operations were performed with a Failing 1500 rig and wet-drilling procedure. When claystone or siltstone was encountered, a continuous sampling method was conducted with a Pitcher sampler, which consists of a four inch diameter Shelby tube that advances slightly ahead of a rotating core barrel, (see Department of Civil Engineering, University of Alberta River Bank Stability Report, 1968, for complete details on this sampler). The Pitcher sampler has been used successfully in soft rocks of the Edmonton Formation (Department of Civil Engineering, 1968; Pennell, 1969), of the Smoky River Group in northern Alberta (Hayley, 1968), and of the Belly River Formation east of Edmonton. However, in the Paskapoo Formation and the Saunders Group in the western portion of the study area numerous breakdowns and drilling delays resulted from excessive wear on the sampler caused by the highly indurated bedrock.

Analytical Procedures

The samples were subjected to the series of analyses and tests listed in Table II. An attempt was made to subject all of the samples to each test (except the direct shear test), but it was necessary to allow the following exceptions:

TABLE II

LIST OF TESTS PERFORMED ON FINE-GRAINED ROCKS FROM CENTRAL ALBERTA

SAMPLE NUMBER	TYPE OF SAMPLE	DENSITY	WATER CONTENT	ATTERBERG LIMITS	HYDROMETER ANALYSIS	SLAKING AND WET-DRY TESTS	X-RAY DIFFRACTION	CHEMICAL TESTS	THIN SECTION ANALYSIS	DIRECT SHEAR TEST
PAK-1	Outcrop	X	X	X	X	X	X	X	X	
-2	"	X	X	X	X	X	X	X	X	
SRW-39	Corehole	X	X	X	X	X	X	X	X	X
-52	"	X	X	X	X	X	X	X		
-53	"	X	X	X	X	X	X	X	X	X
MC-1	Outcrop	X	X	X	X	X	X	X	X	
-2	"		X	X	X	X	X	X		
LA-9	Corehole	X	X	X	X	X	X	X	X	
-9A	"	X	X	X	X	X	X	X	X	X
RB-1[1]	"	X	X	X	X		X	X	X	
-2[1]	"	X	X	X	X		X	X	X	
-3[1]	"	X	X	X	X		X	X	X	
-1A[1]	"	X	X	X	X		X	X		X
-2A[1]	"	X	X	X	X		X	X		X
-3A[1]	"	X	X	X	X		X	X		X
AGT-1	"	X	X	X	X	X	X	X	X	
-2	"	X	X	X	X		X	X	X	
-3	"	X	X	X	X	X	X	X	X	
-4	"	X	X	X	X	X	X	X	X	
DL-1	Outcrop	X	X	X	X	X	X	X		
-2	"	X	X	X	X	X	X	X	X	
-3	"	X	X	X	X	X	X	X	X	
-4	"	X	X	X	X	X	X	X	X	
-5	"	X	X	X	X	X	X	X	X	
-6	"		X	X	X	X	X	X	X	
W-1	Corehole (air dried)			X	X		X	X	X	
-2	"			X	X		X	X	X	
-3	"			X	X		X	X	X	
-4	"			X	X		X	X	X	
-5	"			X	X		X	X	X	
-6	"			X	X		X	X	X	
-7	"			X	X		X	X	X	
-8	"			X	X		X	X	X	
-9	"			X	X		X	X	X	
M-1	Corehole (air dried)			X	X		X	X	X	
-2	"			X	X		X	X	X	
-3	"			X	X		X	X	X	
-4	"			X	X		X	X	X	
-5	"			X	X		X	X	X	
-6	"			X	X		X	X	X	

SAMPLE NUMBER	TYPE OF SAMPLE	DENSITY	WATER CONTENT	ATTERBERG LIMITS	HYDROMETER ANALYSIS	SLAKING AND WET-DRY TESTS	X-RAY DIFFRACTION	CHEMICAL TESTS	THIN SECTION ANALYSIS	DIRECT SHEAR TESTS
P- 1	Outcrop	X	X	X	X	X	X	X	X	
- 2	"	X	X	X	X	X	X	X	X	
- 3	"	X	X	X	X	X	X	X	X	
- 4	"	X	X	X	X	X	X	X	X	
- 6	"							X		
- 7	"	X	X	X	X	X	X	X	X	
- 33	Corehole	X	X	X	X	X	X	X	X	
- 54	"	X	X	X	X	X	X	X	X	X
- 69	"	X	X	X	X	X	X	X	X	X
- 87	"	X	X	X	X	X	X	X	X	
-116	"	X	X	X	X	X	X	X	X	
MRE-1	Outcrop	X	X	X	X	X	X	X	X	
-2	"	X	X	X	X	X	X	X	X	
-4	"		X	X	X		X	X		
-5	"	X	X	X	X	X	X	X	X	
SR-1	"	X	X	X	X	X	X	X	X	
MRR- 0	"	X	X	X	X	X	X	X	X	
- 1	"	X	X	X	X	X	X	X	X	
- 2	"	X	X	X	X	X	X	X	X	
- 3	"	X	X	X	X	X	X	X	X	
- 4	"	X	X	X	X	X	X	X	X	
- 9	"	X	X	X	X	X	X	X	X	
-10	"	X	X	X	X	X	X	X	X	
-45	Corehole	X	X	X	X	X	X	X	X	X
-74	"	X	X	X	X	X	X	X	X	X
C-1	Outcrop	X	X	X	X	X	X	X	X	
-2	"	X	X	X	X	X	X	X		
MRH-1	"	X	X		X	X	X	X	X	
-2	"	X	X	X	X	X	X	X	X	
-3	"	X	X	X	X		X	X		
-4	"	X	X	X	X	X	X	X	X	
-5	"	X	X	X	X	X	X	X	X	
MRM-1	"	X	X	X	X	X	X	X	X	
-2	"	X	X	X	X	X	X	X	X	
-3	"	X	X	X	X	X	X	X	X	
-4	"								X	
MP-1	"	X								
-2	"	X								
-3	"	X								

[1] Data from River Bank Stability Report, Dept. of Civil Engineering, Univ. of Alberta, 1968.

(1) bulk density and water content determinations could not be made on air-dried samples from the Wizard Lake and McLeod River coreholes (W and M series of samples);

(2) certain samples could not be thin-sectioned owing to their friability;

(3) only density and wet-dry cycle measurements were performed on the highly indurated Lower Cretaceous samples (MP series) from Cadomin - these samples were not considered to form part of the investigation proper.

Direct shear tests were performed only on "undisturbed" samples containing their natural water content from the three coreholes drilled specifically for this purpose. The data obtained from these samples (SRW, P, and MRR series) were augmented by data obtained from similar tests performed on corehole samples from the Edmonton area (RB and LA series) by staff of the University of Alberta, Department of Civil Engineering (1968) and a colleague, D. G. Pennell (1969).

CHAPTER V

PETROGRAPHIC AND ENGINEERING PROPERTIES

The fundamental petrographic properties of clastic (i.e. fragmental) sedimentary rocks are texture, composition, and structure. Texture can be divided into four sub-properties (Griffiths, 1967): particle size and shape (which are properties of the individual grains), and packing and orientation (which describe the position or arrangement of grains in the rock aggregate). Composition refers to the make-up of the individual particles and is expressed usually in the terms of the proportions of minerals that constitute the aggregate rock specimen. Structure is a derived property that refers to textural or compositional inhomogeneities in a rock and thus may or may not be present, depending on the scale at which the materials are viewed.

In addition to these fundamental properties, rocks possess a number of mass or bulk properties such as colour, void ratio, hardness, etc. of which bulk density and plasticity are of particular interest to the engineer. These properties are related to the fundamental petrographical attributes of sedimentary rocks, one of the objectives of this investigation being to define these interrelationships.

Texture

Texture is the size, shape, orientation, and packing of the particles in a sedimentary rock. Of these four properties grain size and, to a lesser extent, grain orientation can be measured and used for classification of fine-grained rocks. Limitations of available laboratory techniques make grain shape and orientation exceedingly difficult to determine.

Grain Size

Grain size analysis of fine-grained sedimentary rocks show that they vary widely in the percentages of sand-, silt-, and clay-size material. Pettijohn (1957) states that a high proportion of silt-sized material is found in these rocks and that true claystones or shales are uncommon.

The fine-grained nature of siltstones and shales has hindered their study by petrographers since only particles larger than fine silt are easily resolved under the optical microscope. Grain-size analyses are usually done by a combination of sieve and sedimentation techniques. The interpretation of the resulting grain-size distribution curves is hampered by the inherent limitations of these techniques as well as by the laminated structure of many siltstones and claystones. The laminations usually consist of alternating layers of silt and clay a few millimetres to a few centimetres

thick, with the result that slight variation in the position of a sample will markedly affect the median grain size and the shape of the size-distribution curve.

Descriptive terminology for grain shape, e.g. roundness, is employed in studies on coarse sands, conglomerates, etc., however its application for fine-grained sedimentary rock is limited by the grain size. Microscopic study can reveal the general shape of the coarse silt plus sand fraction and the shape of the clay minerals can be inferred from available knowledge (Grim, 1953).

Grain Size Determination

Grain size determinations were performed by the hydrometer technique in accordance with A.S.T.M. Designation D 422-63 with the following modifications. All samples were broken down by a freeze-thaw technique rather than by a drying and crushing procedure. Dispersion of the soil particles was accomplished by adding 10 to 30 cc. of 10 per cent sodium hexametaphosphate to the suspension; the quantity was dependent on the tendency of the sample to flocculate. In some cases, washing with distilled water was required to reduce the salt content and promote dispersion.

Grain-size analyses require the fine-grained rock to be broken down into "primary particles" and the freeze-thaw technique is believed to approach this ultimate goal better than grinding. There is no apparent reason why an indurated material subjected to air-drying and grinding should break

along particle boundaries. The grinder does not select the surfaces of fracture but planes of weakness determined by the direction of grinding forces thus, they may cut through a particle. However, a rock subjected to internal forces generated by freezing and thawing, which are not restricted in their direction of force application may result in a greater part of the sample breaking down along interparticle contacts.

The percentage of sand- plus coarse silt-sized particles also was determined from point counts on thin-sections. In addition, the predominant size of silt-sized particles, as noted in thin sections, was rated as coarse or medium for each sample. Fine silt is too small to be readily discernible in thin sections of conventional thickness (30 μ).

Results

Textural classification is based upon the Massachusetts Institute of Technology scale, commonly accepted by civil engineers. The results of the hydrometer analysis and petrographic point counts are presented in Table III, columns 2 - 4 and Table IV, columns 12 - 13, respectively.

The average percentages of sand-, silt-, and clay-size detritus in fine-grained soft rocks of central Alberta is 14 per cent sand, 55 per cent silt, 31 per cent clay, which averages are comparable to the average "shale" as reported by Pettijohn (1957). However, there is considerable deviation

TABLE III

SUMMARY OF PETROGRAPHIC, ATTERBERG LIMITS, AND BULK PROPERTIES DATA FOR FINE-GRAINED ROCKS FROM CENTRAL ALBERTA

SAMPLE NUMBER	TEXTURE			COMPOSITION											PLASTICITY					BULK PROPERTIES					DISTANCE	DEPTH	LITHOLOGY
	Sand	Silt	Clay	Mont.	Ill.	Kaol.	Chl.	Na^+	K^+	Ca^{++}	Mg^{++}	P.W.S.	Org.	Carb.	w_L	w_p	I_p	A	I_L	γ_t	e	w_N	C.E.C.	W.D.R.			
	%	%	%	%	%	%	%	meq	meq	meq	meq	meq	%	%						pcf		%	meq		mi.	ft.	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
PAK-1	12	43	40	28	6	6	0	4	1	20	7	6	0.8	0	56	19	37	0.94	0	123	.62	20	25	7	204	7	clayey siltstone
-2	23	47	30	18	6	0	6	5	1	22	7	3	1.3	0	54	24	30	1.02	0	128	.64	23	32	7	204	11	sandy clayey siltstone
SRW-39[1]	10	54	36	14	11	4	7	14	1	12	4	4	1.4	0	61	21	40	1.10	-0.16	136	.42	14	27	1	197	39	clayey siltstone
-52	12	48	40	26	6	0	8	19	1	16	4	7	1.6	0	100	26	74	1.86	-0.14	135	.43	16	33	NA	197	52	clayey siltstone
-53[1]	28	49	23	15	3	0	5	19	1	16	4	7	1.6	0	61	24	37	1.52	-0.27	132	.37	14	33	NA	197	53	sandy clayey siltstone
MC-1	8	52	40	20	10	4	6	14	1	17	6	7	0.7	0	90	23	67	1.66	-0.03	122	.71	21	30	7	196	22	clayey siltstone
-2	16	52	32	16	8	2	6	12	1	13	4	8	0.5	0	91	20	71	2.22	-0.07	NA	NA	25	22	1	196	25	clayey siltstone
RB-1	15	35	50	48	2	0	0	4	1	74	12	21	0.4	0	147	49	98	1.96	-0.05	112	NA	40	69	NA	150	113	silty claystone
-2	28	15	57	57	0	0	0	2	1	71	40	43	0.5	0	182	51	131	2.30	-0.07	103	NA	60	71	NA	150	1	bentonite
-3	33	45	22	17	4	0	1	3	1	38	9	10	1.0	0	62	31	31	1.41	-0.06	115	.87	29	41	NA	150	110	sandy clayey siltstone
LP-9	4	24	72	61	11	0	0	34	1	30	3	19	0.5	0	192	42	150	2.07	-0.07	NA	NA	31	50	1	155	99	silty claystone
-9A[1]	5	27	68	54	14	0	0	34	1	30	3	19	0.5	0	227	51	176	2.58	-0.09	112	.99	36	50	7	155	95	silty claystone
AGT-1	10	53	37	20	11	6	0	1	1	34	11	9	1.0	0	45	30	15	0.41	-0.53	129	.57	22	38	6	150	69	clayey siltstone
-2	10	75	15	12	2	0	1	1	1	34	12	10	1.1	0	60	30	30	2.00	-0.50	140	.42	15	38	NA	150	85	siltstone
-3	7	51	42	34	6	0	2	13	1	28	6	15	1.8	0	129	34	95	2.51	-0.17	135	.45	18	33	11	150	118	clayey siltstone
-4	10	53	37	28	6	0	3	26	1	25	4	13	1.1	0	113	31	82	2.25	-0.17	137	.42	17	44	7	150	143	clayey siltstone
DL-1	41	40	19	10	7	0	2	1	1	24	12	3	1.3	0	42	29	13	0.67	-0.77	131	.52	19	34	6	135	8	sandy siltstone
-2	25	48	27	19	5	0	3	1	1	23	16	11	1.4	0	46	27	19	0.72	-0.53	123	.53	17	34	6	135	12	sandy clayey siltstone
-3	7	73	20	13	4	3	0	1	1	26	13	6	0.8	0	48	27	21	1.05	-0.43	120	.51	19	23	10	135	22	clayey siltstone
-4	20	59	21	18	2	0	1	1	1	28	13	9	0.5	0	45	24	21	0.98	-0.14	126	.61	21	33	6	135	29	clayey siltstone
-5	9	70	21	17	4	0	0	2	1	32	15	12	0.7	0	48	30	18	0.84	-0.50	129	.57	21	38	11	135	36	clayey siltstone
-6	23	42	35	33	2	0	0	4	1	76	31	33	0.2	0	77	58	19	0.52	0.21	NA	NA	62	79	NA	135	38	bentonite
W-1[2]	12	68	20	13	6	0	1	1	1	89	12	71	0.2	5.3	50	27	23	1.14					32		120	23	clayey siltstone
-2	35	47	18	5	5	5	2	3	1	44	4	42	0.2	9.6	29	18	11	0.54					9		120	101	sandy siltstone
-3	6	53	41	8	16	13	4	12	1	14	5	7	1.4	0	68	22	46	1.11					25		120	167	clayey siltstone
-4	0	52	48	29	12	2	5	16	1	15	4	7	1.4	0	88	27	61	1.28					29		120	234	clayey siltstone
-5	4	48	48	24	17	5	2	21	1	17	4	6	0.4	0	74	24	50	1.03					37		120	302	clayey siltstone
-6	8	17	75	75	0	0	0	67	1	33	4	49	0.5	0.3	286	31	255	3.40					57		120	334	claystone
-7	12	41	47	28	17	5	2	33	1	24	4	16	0.3	0	93	38	55	1.17					45		120	345	silty claystone
-8	1	46	53	29	16	5	3	18	1	15	4	7	1.3	0	101	24	77	1.45					31		120	477	silty claystone
-9	14	47	39	27	8	4	0	23	1	18	3	12	1.0	0	139	23	116	2.99					34		120	496	clayey siltstone
M-1[2]	17	51	32	32	0	0	0	12	3	68	14	41	0.2	2.4	88	28	60	1.88					55		112	43	clayey siltstone
-2	6	52	42	21	13	4	4	12	1	17	9	15	0.6	0	77	26	51	1.21					25		112	61	clayey siltstone
-3	24	55	21	11	8	0	2	6	1	100	9	99	0.0	11.0	49	19	30	1.41					14		112	70	sandy clayey siltstone
-4	2	48	50	8	30	10	2	12	1	14	4	8	1.0	0	79	24	55	1.09					23		112	171	silty claystone
-5	5	45	50	10	30	5	5	13	1	18	9	16	1.6	0	74	24	50	1.00					25		112	184	silty claystone
-6	11	65	24	20	2	0	2	11	1	33	5	27	0.5	2.3	63	21	42	2.09					22		112	114	clayey siltstone
P-1	6	46	48	14	24	0	10	1	1	55	14	37	0.5	1.2	44	31	13	0.28	-1.08	136	.48	17	33	13	112	47	silty claystone
-2	17	64	19	15	3	0	1	1	2	40	11	10	0.9	0	52	33	19	0.99	-0.53	126	.64	23	44	6	112	82	clayey siltstone
-3	12	65	23	12	9	0	0	4	1	32	9	7	0.3	0	40	27	13	0.54	-0.93	135	.45	15	39	8	112	109	clayey siltstone
-4	7	72	21	5	11	3	2	1	1	37	7	27	0.4	1.9	39	27	12	0.56	-1.06	140	.39	14	17	10	112	61	clayey siltstone
-7	23	66	11	6	4	0	1	1	1	24	5	2	0.2	0	34	27	7	0.56	-1.71	138	.43	15	30	12	112	90	sandy siltstone
-33	23	57	20	10	7	0	3	1	2	36	11	2	0.3	0	52	23	29	1.44	-0.34	131	.60	13	47	8	112	33	sandy siltstone
-54[1]	0	70	30	10	12	3	5	1	1	38	5	28	0.5	1.5	45	26	19	0.63	-0.74	143	.33	12	16	11	112	54	clayey siltstone
-69[1]	18	65	17	8	7	0	2	1	1	33	5	2	0.3	0	46	27	19	1.10	-0.74	140	.37	13	37	14	112	69	sandy siltstone
-87	30	47	23	5	15	0	3	4	1	24	4	2	0.2	0	44	27	17	0.73	-0.83	142	.36	12	30	13	112	87	sandy clayey siltstone
-116	10	52	38	11	21	0	5	15	1	21	4	2	0.1	0	49	21	28	0.74	-0.36	145	.32	11	38	17	112	116	clayey siltstone
MRE-1	4	61	35	5	21	5	4	1	1	39	12	33	0.8	1.7	36	26	10	0.29	-1.50	144	.32	11	19	14	77	61	clayey siltstone
-2	30	49	21	12	8	0	1	1	2	50	30	21	0.4	0.3	57	39	18	0.88	-0.61	125	.77	28	62	6	77	67	sandy clayey siltstone
-4	0	60	40	10	24	4	2	14	1	70	12	73	0.2	1.7	69	23	46	1.17	-0.39	NA	NA	41	24	NA	77	115	clayey siltstone
-5	10	70	20	6	10	0	4	8	1	39	3	32	0.2	2.4	82	22	60	2.96	-0.18	145	.27	11	19	18	77	97	clayey siltstone
SR-1	7	53	40	8	26	0	6	1	1	23	6	1	0.3	0	55	22	33	0.81	-0.33	144	.35	11	31	13	76	1	clayey siltstone
MRR-0	1	79	20	6	10	2	2	1	1	57	4	36	0.5	2.6	42	25	17	1.36	-0.71	144	.36	13	26	18	59	26	siltstone
-1	14	46	40	6	24	4	6	1	1	35	6	14	0.9	0.3	50	24	26	0.66	-0.46	147	.32	12	29	15	59	34	clayey siltstone
-2	12	70	18	8	7	0	3	1	1	26	8	6	0.3	0	39	21	17	0.98	-0.65	145	.30	10	28	15	59	41	clayey siltstone
-3	14	61	25	5	13	3	4	1	1	45	5	34	0.3	1.8	42	26	16	0.67	-0.8	147	.34	12	23	18	59	45	clayey siltstone
-8	12	72	16	6	7	0	3	1	1	20	9	4	0.2	0	32	21	11	0.70	-1.13	149	.25	8	25	17	59	48	clayey siltstone
-9	15	68	17	7	8	1	2	1	1	38	5	26	0.4	2.6	37	21	16	0.93	-1.35	145	.26	9	19	20	59	127	clayey siltstone
-10	22	50	28	7	18	0	3	1	1	43	13	4	0.1	0	43	25	17	0.61	-1.24	146	.34	12	29	11	59	129	sandy clayey siltstone
-45[1]	38	43	19	5	12	1	1	1	1	21	9	4	0.2	0	43	23	20	0.50	-1.57	150	.22	7	27	15	59	45	clayey siltstone
-74[1]	10	82	8	5	2	0	1	2	1	38	7	29	0.1	2.4	57	24	33	4.14	-2.30	148	.28	9	19	17	59	74	siltstone
C-1	10	76	14	4	6	3	1	1	1	34	10	24	0.8	2.2	31	23	8	0.54	-1.30	149	.23	8	20	17	37	NA	siltstone
-2	12	57	31	5	20	3	2	1	1	19	19	5	0.4	0	31	22	9	0.29	-0.95	147	.19	10	24	11	37	NA	clayey siltstone
MRH-1	27	50	23	11	9	0	2	1	1	29	13	5	2.8	0	0	0	0	0	0	128	.47	17	36	8	37	102	sandy clayey siltstone
-2	15	52	32	5	21	3	3	1	1	19	4	3	0.7	0	43	22	21	0.65	-1.64	147	.26	9	21	14	37	112	clayey siltstone
-3	15	55	30	24	5	0	1	29	1	28	3	20	0.5	0	94	33	61	2.05	-2.53	146	.25	9	41	NA	37	122	clayey siltstone
-4	15	73	12	4	6	1	2	1	1	23	12	10	1.2	0	36	24	12	0.93	-0.96	139	.29	13	26	11	37	135	sandy siltstone
-5	4	71	25	10	10	3	3	7	1	19	7	11	0.9	0	53	23	30	1.18	-1.70	138	.41	14	23	11	37	200	clayey siltstone
MRM-1	16	61	23	23	0	0	0	31	1	63	3	13	0.1	0	54	36	18	0.77	-0.86	127	.62	23	85	6	33	NA	bentonite
-2	15	47	38	38	0	0	0	38	2	65	5	11	0.2	0	91	35	45	1.19	-1.14	107	NA	41	79	1	33	NA	bentonite
-3	42	46	11	7	3	0	1	1	1	65	7	46	0.2	0	34	27	7	0.67	-1.00	152	.20	7	27	9	33	NA	sandy siltstone
MP-1	Only density measurements available for MP samples																			160				20	20		"shale"
-2																				160				19	20		"shale"
-3																				160				20	20		"shale"

[1]Direct shear-tested samples. [2]Air-dried samples, density data not available.

KEY - Cols. 5-8 (Montmorillonite, illite, kaolinite, chlorite); Cols 9-13 (Sodium ion, potassium ion, calcium ion, magnesium ion, pore water salt concentrations in milliequivalents); Col. 14 (Organic matter); Col. 15 (Carbonate); Cols. 16-20 (Liquid limit, plastic limit, plasticity index, activity, liquidity index); Cols. 21-25 (Bulk density in pounds per cubic foot, void ratio, natural water content, cation exchange capacity in milliequivalents, wet-dry cycle rating); NA = not available; Cols. 26, 27 (Distance in miles, depth in feet).

TABLE IV

PETROGRAPHIC PROPERTIES OF FINE-GRAINED SOFT ROCKS OF CENTRAL ALBERTA AS DETERMINED FROM THIN SECTIONS

SAMPLE NUMBER	DISTANCE (miles)	< 20 MICRONS (%)[1]	MONTMORILLONITE (%)[2]	COLOR	STRUCTURES: PRIMARY			STRUCTURES: SECONDARY	STRUCTURES: INDUCED (Fractures)		TEXTURES			COMPOSITION						
					Homo.	Lamin.	Pell.		Type	Stain.	% >20μ	Silt size	Clay orient.	Q.+F.	R.F.	Micas	Mont.	Org.	Pyr.	Carb.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
PAK-1	204	25	28	Br-Gr	X				R		10	C	0	Ab	P		P	Ab		
-2	204	38	18	Gr		F			Pa, Pe	X	20	C	0	Ab	P	P		Ab	P	
MC-1	196	24	20	Gr		F			R		15	C	1	Ab	P	P	P			Ab
LA-9	155	8	61	Gr		S			Pa, Pe	X	1	M	2	P		P	Ab	P		
LA-9A	155	8	54	Br-Gr	X				R		0	Sh	2			P	Ab		P	
RB-1	150	NA	48	Gr	X				R	X	0		2, NU				Ab		P	P
-2	150	NA	57	Gr	X			Brecc.	R	X	0		2, NU				Ab		P	P
-3	150	NA	17	Br-Gr		F	X				15	C	3	P	P		P		P	P
AGT-1	150	25	20	Br	X			Brecc.	R		0		5, NU				P			
-2	150	30	12	Br-Gr		S		Slump	Pa		40	C	1, NU	Ab	P	P	P	P	P	P
-3	150	18	34	Br		S			Pa	X	25	C-M	1	Ab	P	P	Ab	P		Ab
-4	150	31	28	Br-Gr		S			R		20	C-M	2	Ab		P	Ab	P	P	
DL-1	135	50	10	Br		F			Pa		10	M	1	P		P	P	P	P	P
-2	135	38	19	Gr		F			R	X	1	C	2	P			P	P		P
-3	135	27	13	Gr		F			Pa, Pe		10	C	1	Ab	P	Ab		P	P	Ab
-4	135	40	18	Gr-Br		F			Pa, Pe		1	M	1				P	Ab	P	Ab
-5	135	23	17	Gr		F	X		Pa, Pe	X	1	M	4, NU	P			P	P	P	P
W-1	120	34	13	Gr			X		Pa	X	40	C	1, NU	P		P	P	P	P	P
-2	120	53	5	Br-Gr		S			Pa		55	C	0	Ab	P	P		P	P	Ab
-3	120	10	8	Gr		F					10	M	1			Ab		P	P	P
-4	120	3	29	Br		F	X				0		1			P	P	Ab	P	
-5	120	15	24	Br-Gr			X		Pa		10	M	2, NU	P		P	P	P	P	
-6	120	10	75	Br		F		Slump	Pa		1	C	3, NU	P		P	Ab			
-7	120	22	28	Br		F			Pa		5	M	4, NU	P			Ab		P	
-8	120	5	29	Gr		F			Pa		1		2, NU			P	P	P	P	
-9	120	31	27	Br-Gr		F					25	C	1	P	P	P	P	Ab	P	P
M-1	112	34	32	Gn-Gr		F					10	M	4, NU	P		Ab	P			P
-2	112	7	21	Gr-Gn		S			Pa		5	M	5, NU	P		P	P	P	P	
-3	112	43	11	Gr		S	X		Pa		15	C	2, NU	P	P	P	P	P	P	Ab
-4	112	4	8	Gn-Gr		S			Pa		5	M	5			P	P	P		
-5	112	7	10	Br-Gr		S			Pa		1		1, NU	P		P		Ab	P	P
-6	112	30	20	Br-Gr		S		Slump	Pa		5	M	1	P		P	P	P	P	Ab
P-1	112	8	14	Br-Gr	X				Pa	X	0		4				P	Ab		P
-2	112	43	15	Gr		S			Pa, Pe	X	10	M	2, NU	P	P	Ab	P	P		P
-3	112	30	12	Gr-Gn	X			Brecc.	R		10	M	2, NU	P		P	P		P	
-4	112	20	5	Br-Gr			X		Pa		40	C	5, NU	P		Ab	P	P	P	
-6	112	NA	NA	Gn-Gr		F		Brecc.	R		0		5, NU				P		P	
-7	112	47	6	Gr-Gn		F	X		Pa		10	C	2, NU	P	P	Ab	P	P	P	
-33	112	38	10	Gn-Gr		F					0		2, NU			Ab				
-37	112	44	15	Gn-Gr		F	X		Pa	X	13	C	1, NU	P	P	P	P		P	
MRE-1	77	5	5	Br-Gr		F	X		Pa		10	M	1			P	P	P	P	Ab
-2	77	41	12	Gn		F			Pa	X	20	C	3	P		P	P	P	P	
-5	77	22	6	Gr		S		Slump	Pa, Pe		15	C-M	1, NU	P		P		P	P	Ab
SR-1	76	15	8	Br-Gr			X				5	M	3, NU	P		Ab	P		P	
MRR-0	59	18	6	Gr-Br		S			Pa		25	C	1	P		P	P	P	P	P
-1	59	20	6	Br-Gr	X				Pa		0		2, NU				P	P	P	
-2	59	28	8	Br	X				Pa	X	13	C	2	P	P	Ab	P	P	P	
-3	59	25	5	Gr		F			R		10	M	1, NU	P		P	P	P	P	Ab
-4	59	55	6	Br			X		Pa	X	50	C	1, NU	Ab	P	P	P		P	P
-9	59	50	7	Gr-Br		F			Pa		55	C	0	Ab	P	P	P		P	P
-10	59	27	7	Br-Gr	X				R		0		2, NU				P	P	P	P
C-1	37	28	4	Br-Gr		S			Pa, Pe		10	M	1	P				Ab	P	Ab
MRH-1	37	45	11	Gr-Br		F			Pa, Pe		25	C	2, NU	P	F	P	P	Ab	P	
-2	37	22	5	Gn-Gr	X				Pa		0		1						P	
-4	37	37	4	Br-Gr		F			R	X	20	C	1	P	P	P		Ab	P	P
-5	37	15	10	Br-Gr		S			Pa, Pe		30	C-M	1	Ab	P	P	P	P	P	P
MRM-1	33	42	23	Gr	X				R	X	5	Sh	1, NU	P		P	Ab		P	
-2	33	30	38	Br	X				R	X	13	Sh	1, NU	P	P	P	Ab	P		
-3	33	73	7	Gr		S		Slump	Pe	X	20	C	1, NU	Ab	P	P		Ab	P	P
-4	33	NA	NA	Gn-Gr			X		Pa		10	C	1, NU	Ab	P	P	P		P	

[1]From hydrometer analysis. [2]From grain size and X-ray data.

KEY - Cols. 3, 4: NA = not available; Col. 5: Br = brown, Gr = grey, Gn = green; Col. 6 (homogeneous): X = present; Col. 7 (Laminated): F = faint, S = strong; Col. 8 (Pelleted): X = present; Col. 9: Brecc. = brecciated; Col. 10: R = random, Pa = parallel to bedding, Pe = perpendicular to bedding; Col. 11 (Staining): X = present; Col. 12: silt (> 20 microns) content; Col. 13: M = medium, C = coarse, Sh = shard texture; Col. 14 (orientation): NU = nonuniform; Cols. 15-21 (Quartz plus feldspars, rock fragments, micas, montmorillonite, organic matter, pyrite, carbonates): P = present, Ab = abundant.

from this average across the study area, as indicated by the ternary diagram (Figure 6) on which the proportions of sand-, silt-, and clay-size material as determined from hydrometer analyses have been plotted. The Belly River Formation rocks are the most homogeneous in grain size distribution (sandy and clay siltstones), but this apparent lack of variation may be due to the limited number of samples analysed. The Edmonton Formation[1] rocks show considerable variation in grain size and include the only samples with a clay percentage of more than 40 per cent. In contrast the rocks from the western portion of the study area (Saunders Group) are composed predominatly of silt-sized material. The tendency for higher percentage of clay-size material in samples from the eastern portion of the study area can be attributed to the selective sorting action of the streams and other agencies which carried the detritus from the western area. In general, however, the majority of the fine-grained rocks in the study area contains large proportions of silt-sized material, sufficient to classify them as siltstones.

The thin section study substantiates the results of the hydrometer analysis; Table IV, column 13 shows that nearly all of the samples contain an abundance of either coarse- or medium-size silt particles.

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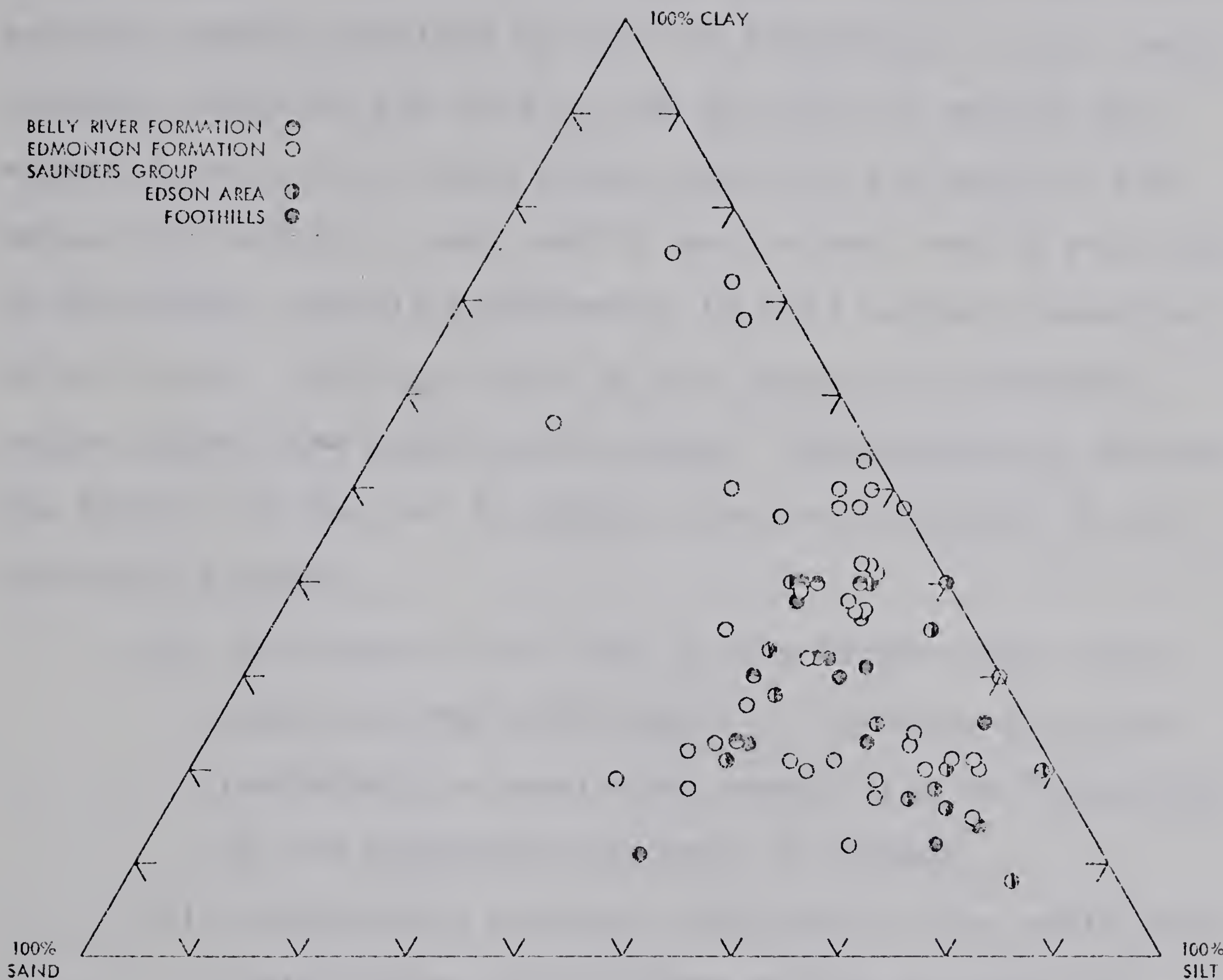
[1] Edmonton Formation here may also include basal Paskapoo beds at Entwistle, Wizard Lake and McLeod River, south of Whitecourt.



TERNARY DIAGRAM OF PER CENTS SAND, SILT, AND CLAY OF THE ALBERTA ROCKS

FIGURE 6

However, an examination of the percentages of sand plus coarse silt sizes as determined from the hydrometer analysis and the petrographic analysis (Tables III and IV, columns 3 and 12, respectively) shows that variations up to 40 per cent exist between results obtained by the two techniques. More specifically, about 10 per cent of the two sets of values are within 5 per cent of each other, about 50 per cent of the values are within 10 per cent of each other, and 45 per cent of the values exhibit differences in silt content exceeding 10 per cent. In 80 per cent of the cases the hydrometer values exceed the point count values. The variation between the results of the two techniques can be attributed to the following factors:

(1) Breakdown of the rock by the freeze-thaw cycle technique was not complete. Consequently, the percentage of sand plus coarse silt as determined by the hydrometer analysis is higher.

(2) Considerable verticle variation in the grain size distribution of the rocks exists on both the macroscopic and the microscopic scale. Hence the two samples selected from the same locality for grain size determination may have different lithologies owing to this lamination effect.

Of the two explanations, the first appears to be the dominant factor in the light of the difficulty in breaking down some of the samples and the generally higher values

obtained from the hydrometer analyses. Thus, it appears that the effectiveness of the freeze-thaw cycle technique is still open to question and that in order to fully evaluate the procedure closer control over local (micro) variation in lithology must be exercised. The influence of the number of freeze-thaw cycles to which a sample is subjected also may reveal the relative efficiency of the procedure.

Grain Shape

Particle "shape" is usually described in terms of grain sphericity and grain roundness (Pettijohn, 1957). No attempt was made to determine either of these properties on a systematic basis, but the following observations can be made.

In terms of sphericity, the clastic constituents of the fine-grained rocks under consideration can be subdivided in two groups: silt-sized nearly equidimensional quartz, feldspar, and rock fragment grains and silt- to clay-sized platy mica and clay mineral particles. The quartz and feldspar grains are angular, suggesting that the detritus was deposited relatively quickly after erosion. Micas appear as lath-like plates or fine shreds in thin sections cut perpendicular to the bedding, although often distorted owing to their flexible nature.

Variations in particle size and shape impart various overall textural effects to the rocks in thin sections, as noted in the following photomicrographs:

Plate 1, Figure 1:	Coarse-grained, distorted, mica plate and coarse grained, silt-sized quartz fragment floating in clay matrix.
Plate 1, Figure 2:	Fine-grained, shredded mica "floating" in silty clay matrix.
Plate 4, Figure 1:	High percentage of coarse silt-sized material in clay matrix.
Plate 4, Figure 2:	High percentage of very fine-grained clay with the odd floating silt grain (bentonite).

The photomicrographs in Plate 5 exhibit a special form of texture termed "shard-texture". Shards in their original state are needle-like or curved spicule-like forms of volcanic glass which alter to montmorillonite through a process known as devitrification. The alteration, however, does not necessarily destroy the original shard shape, hence "shard-ghosts" may be preserved. Figures 1 and 2, Plate 5 are excellent examples of the overall texture which these pseudomorphs impart to a fine-grained bentonitic rock. The bentonitic claystones from the Lesueur slide exhibit an altered shard texture, in which many of the shards have lost their original shape because of the compression of the bentonite

after alteration.

The shape of the shards depends upon the violence of the explosive eruptions of the volcanic vent(s) from which they came (Carozzi, 1960). Plate-like or needle-like glass shards are the result of the fragmentation of the walls of flat lenticular bubbles produced by a less violent volcanic explosion than that which produces more or less spherical bubbles from which curved plates or spicule-forms are derived.

Shard texture in many of the soft rocks in central Alberta confirms the volcanic origin of the vast quantities of montmorillonite and bentonite in these rocks.

Grain Orientation

The orientation of particles in a sedimentary rock is a reflection of depositional processes and environment, and subsequent compression. The measurement of particle orientation has been confined largely to measurements of pebbles and sand grains because silt and clay particles are difficult to resolve under the light microscope in thin sections of conventional thickness. However, the direction and degree of the preferred orientation of aggregates of clay particles may be observed in thin sections with the aid of polarized light, e.g. Mitchell (1956), Morgenstern and Tchalenko (1967, a,b,c,).

Most clay mineral aggregates are birefringent to some degree if they are studied under crossed nicols of the

polarizing microscope with their basal planes perpendicular to the plane of the thin section. That is, the clay particles viewed under crossed nicols transmit zero light intensity when one of the optical axes is parallel to the wave front emerging from the polarizer, and transmit maximum light intensity when the optical axis is at 45 degrees to it. Thus, if an individual clay crystal is rotated through 360 degrees on the stage of a polarizing microscope, four extinction positions and four positions of maximum illumination will be viewed. If an aggregate of clay crystals is studied, the same phenomenon will be observed but total minimum and maximum light intensity will seldom occur owing to different degrees of orientation of the particles. If the clay particles are arranged in a random fashion, no variation in light intensity is observed when the thin section is rotated under crossed nicols. However, if preferred orientation is present, the variation in light intensity will be a function of the degree of orientation.

Procedure

The study of particle orientation was primarly restricted to the clay aggregates because the alignment of sand and coarse silt particles was detected only in the odd instance. An example of alignment of coarser-grained materials is provided by the photomicrograph in Plate 12, Figure 2 where the particles show a tendency for a change in alignment

from parallel to the bedding to parallel to the walls of an infilling.

Aggregate clay particle orientation was determined in the sections cut perpendicular to the plane of the bedding as observed in outcrop or core sections. It was established on the basis of the birefringence properties of clay minerals as described above, the amount of preferred orientation being evaluated by a ranking system. In the initial stages of the study the amount of preferred orientation was rated as the per cent of the total area of the thin section which varied from a position of maximum illumination to extinction. This work revealed that clay particle orientation generally is poorly developed in the fine-grained rocks of central Alberta. The lack of clay aggregate orientation suggested that the adoption of a sophisticated evaluation technique, such as that employed by Morgenstern and Tchalenko (1967 b) was not justified here. The rating system of 0 to 100 per cent also appeared too refined in light of the subjective nature of the technique, with the result that a rating number from zero to five was assigned to each sample, along with a descriptive term, to describe the amount of preferred orientation (Table V). The orientation also was described as uniform or nonuniform according to whether one portion or portions of the thin section displayed a greater degree of orientation than others.

TABLE V

RATING SYSTEM FOR PREFERRED ORIENTATION OF CLAY AGGREGATES

Per Cent Area Oriented	Descriptive Term	Rating Number
0	Nil	0
1 to 19	Very Low	1
20 to 39	Low	2
40 to 59	Medium	3
60 to 79	High	4
80 to 100	Very High	5

The thin sections were cut from samples which were slowly air-dried and then impregnated with Canada Balsam. Most researchers (Mitchell, 1956; Morgenstern and Tchalenko, 1967 a,b) have used Carbowax 6000 to impregnate the saturated sample in order to avoid possible changes in orientation that might be caused by shrinkage during drying. Carbowax 6000 was not used for impregnation of Alberta rocks for in many cases cracking developed, and some rocks, particularly outcrop samples, disintegrated. Sutherland and Singh (1967) reported similar findings in partially saturated clays which had natural water contents close to or less than the shrinkage limit. The same phenomena may have caused the disintegration of the outcrop samples, for all of the samples were not completely saturated (calculated values of the degree of saturation of outcrop samples varied from 82 to 100 per cent). Air-drying of samples from their natural water contents should not alter the orientation of the clay aggregates because the natural water contents of the samples were below (or very close to) the shrinkage limit; hence, no further volume change can occur. Some cracking did appear during the air-drying operation, but it is suggested that the cracks developed at the sites of microfissures inherent to the specimen (e.g. bedding planes).

Results

Clay aggregate orientation is generally poorly developed in fine-grained rocks of central Alberta, with only 20 per cent of the 60 samples examined showing orientation values of 3 or higher (Table IV, column 14). Of these samples 8 out of 13 came from beds adjacent to the Edmonton Formation - Paskapoo Formation contact in the central part of the study area (W, P, and M series), 3 from the lower beds of the Edmonton Formation in the eastern part of the area, and the remaining 2 from the Saunders Group near Edson (Figure 1). None of the Foothills samples show well developed clay particle orientation, including the two samples from Lower Cretaceous beds at Cadomin (not described in Table IV).

Where developed, clay orientation is more commonly of the patchy or non-uniform type, showing up best in samples containing concentrations of very finely crystalline micaceous or montmorillonitic matter, e.g. Plates 1 (Figure 2), 6, 7, and 9 (Figure 2). Plate 7 shows a sharp boundary between two layers of highly oriented material, which may reflect a change in enviromental conditions or possibly composition. In other samples, the boundaries are irregular, with no apparent relation to the bedding; this phenomenon may be due to post-depositional slumping.

Clay aggregate orientation is a commonly observed feature in argillaceous rocks attributed primarily either

to depositional causes (the plates settle parallel to the depositional or bedding surface) or to shear strains imposed by compressive forces (as during compression of the sediments). Why then is particle orientation so poorly developed in the fine-grained near-surface rocks of central Alberta, including those of the highly folded and faulted Foothills region? Possibly the reason is to be found in the hindering action of the silt content of many of the rocks, although the correlation between grain size parameters and orientation is quite low (Table VIII). Moreover thin sections of some samples with high clay contents show little or no preferred particle orientation, which substantiates the statistical evaluation of the data.

An alternative explanation is that the bulk of the clay (montmorillonite, kaolinite, and chlorite) is probably of diagenetic origin, having been deposited originally as volcanic ash. Subsequent alteration of the ash to clay minerals would not necessarily lead to the formation of oriented aggregates, except in those rocks subjected to local stresses contemporaneous with diagenesis. However, the nature and extent of such stresses is uncertain and apparently "random" distribution of clay particle orientation effects in the rocks under consideration remains unexplained.

Mineral Composition

The mineral constituents of most clastic sedimentary rocks are of either a detrital or chemical origin. The detrital constituents are formed by the break-up of some parent source material and are mechanically transported and deposited as discrete grains. The chemical constituents are formed subsequently through alteration or replacement of pre-existing materials or by precipitation in the intergranular pores.

Although the mineral composition of the coarser-grained detrital rocks (conglomerate, sandstone) can be readily determined by macroscopic or thin section techniques, the mineral composition of the finer-grained rocks (siltstone, claystone) is not readily ascertained by these techniques. A knowledge of the chemical composition of these rocks is helpful in some cases but usually cannot be used as a basis for accurate mineral identification (Underwood, 1967). Thus, the investigator must employ a combination of microscopic, X-ray, and size analysis techniques to determine the approximate proportions of mineral constituents in the fine-grained sedimentary rocks.

Procedures

Sand- and Silt-size Detrital Particles

These constituents were identified in thin sections from their morphological and optical properties. Thin sections were cut perpendicular to the bedding from air-dried samples that were impregnated with Canada Balsam and cemented to glass plates by Lakeside 70. Because of the fine-grained nature of the rocks, the materials were grouped into the following classes for estimating their proportions (Table IV, columns 15 to 17, 19, 21): quartz plus feldspar, rock fragments, micas, organic detritus, and carbonates.

The percentages of these groups of constituents were determined for each sample by a point-count technique (involving a mechanical stage that moves the thin section across the field of view at fixed intervals), although the amounts present are reported only as abundant (Ab) or present (P) in Table IV. An "abundant" rating requires that the constituent comprises at least 40 per cent of the sand plus coarse silt fraction of the rock (particles must be greater than 0.02 mm. to be readily identifiable).

Clay Minerals

The proportions of the clay mineral constituents in the rocks were determined from the results of grain size analyses (which yielded the total "clay" content of the rocks)

and X-ray diffraction patterns. The X-ray analyses were performed at the Research Council of Alberta on oriented samples of the clay-sized fraction sedimented onto glass slides. Each slide was run: (a) in an untreated air-dried state, (b) in a glycolated state, and (c) after heating to 500 °C. The diffraction patterns were interpreted along the lines suggested by Johns, Grim and Bradley (1954) and quantitative determinations were based on relative measurements of the peak heights of the diffraction pattern as suggested by D. R. Scafe, Research Council of Alberta.

The criteria for identification of the four major groups of clay minerals may be summarized as:

illite (hydrous mica): by 10 Å reflection in glycolated state

montmorillonite: by 17 Å reflection in glycolated state

chlorite: note presence by 13.2 Å reflection after heat treatment, then measure developed shoulder at 14 Å reflection in glycolated state

kaolinite: by 7.1 Å reflection in glycolated state then subtract the chlorite determination.

The chosen procedure should provide a quantitative determination of the percentage of each clay mineral present in the total clay fraction with an accuracy of approximately ±5 per cent (D. R. Scafe, pers. comm.). However, some error is introduced by the sedimentation techniques of sample

preparation as the finest grains (i.e. montmorillonite) will be the last to settle out with the result that the X-ray pattern will indicate a higher proportion of montmorillonite than actually exists.

The amounts of individual clay mineral types in each sample were calculated by multiplying the percentage of total clay content (hydrometer analyses) by the percentage of a given clay mineral in the clay fraction (X-ray diffraction).

Montmorillonite was the only clay mineral present in sufficiently concentrated amounts to be readily recognized in thin section. The criteria employed for its identification are: (a) light brown (for most Alberta rocks), wispy pattern, (c) generally highly oriented, (d) an appearance best described as "a point of light effect". (G. B. Mellon, pers. comm.).

Organic Carbon and Carbonate Cement

The proportions of these constituents, the first of detrital origin and the second authigenic, were determined by chemical procedures as well as in thin sections. The total carbon content was determined by the use of a "Leko" induction furnace and a gasometric procedure.[1] The carbon dioxide content was established by the use of an absorption train technique described by Hillebrand and Lundell (1953).[2]

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1. Performed by Soil Survey Division, Research Council of Alberta.

2. Performed by Geology Division , Research Council of Alberta.

The organic content was taken to be the difference between the total carbon content and the carbon dioxide content.

The inorganic carbonate content, present mainly as a cement, was determined chemically by the above procedure and semi-quantitatively in thin sections. Neither procedure, especially the chemical one, yields precise results where the amount of carbonate present is low (less than 1 per cent).

Petrographic analyses provide an indication of the origin of the carbonates, i.e., whether present as intergranular fillings (cement) or as discrete grains (detritus). Most carbonates observed in thin-sections are present as irregular crystalline or microcrystalline aggregates and may be assumed to be authigenic (G. B. Mellon, pers. comm.). In some samples, carbonate "fragments" may not be detritus but rather a replacement mineral which has substituted for other grains, e.g. feldspar.

Results

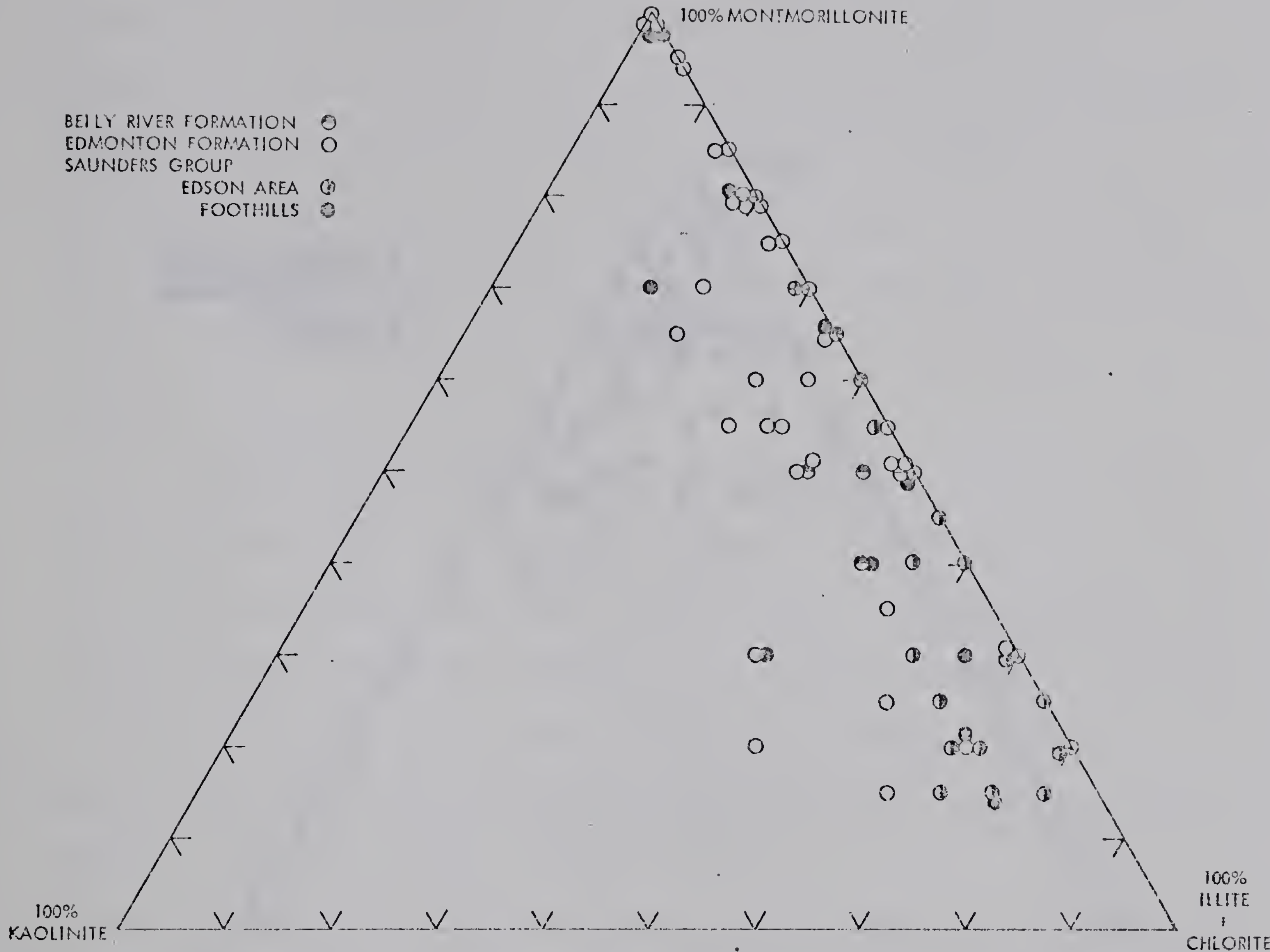
The results of mineral composition analyses were given in Table III (columns 5 to 8, 14, 15) and IV (columns 15 to 21). Photomicrographs which illustrate some of the compositional features are found in Plates 1 to 5, inclusive.

The major constituents of the sand plus course silt fraction are quartz and feldspar and micas (e.g. Plate 4, Fig. 1). Rock fragments, chert, organic detritus, and carbonates are common but are the major constituents in only

a few cases. Most of this material, except organic debris and carbonates, are products of erosion of the original highland source area to the west.

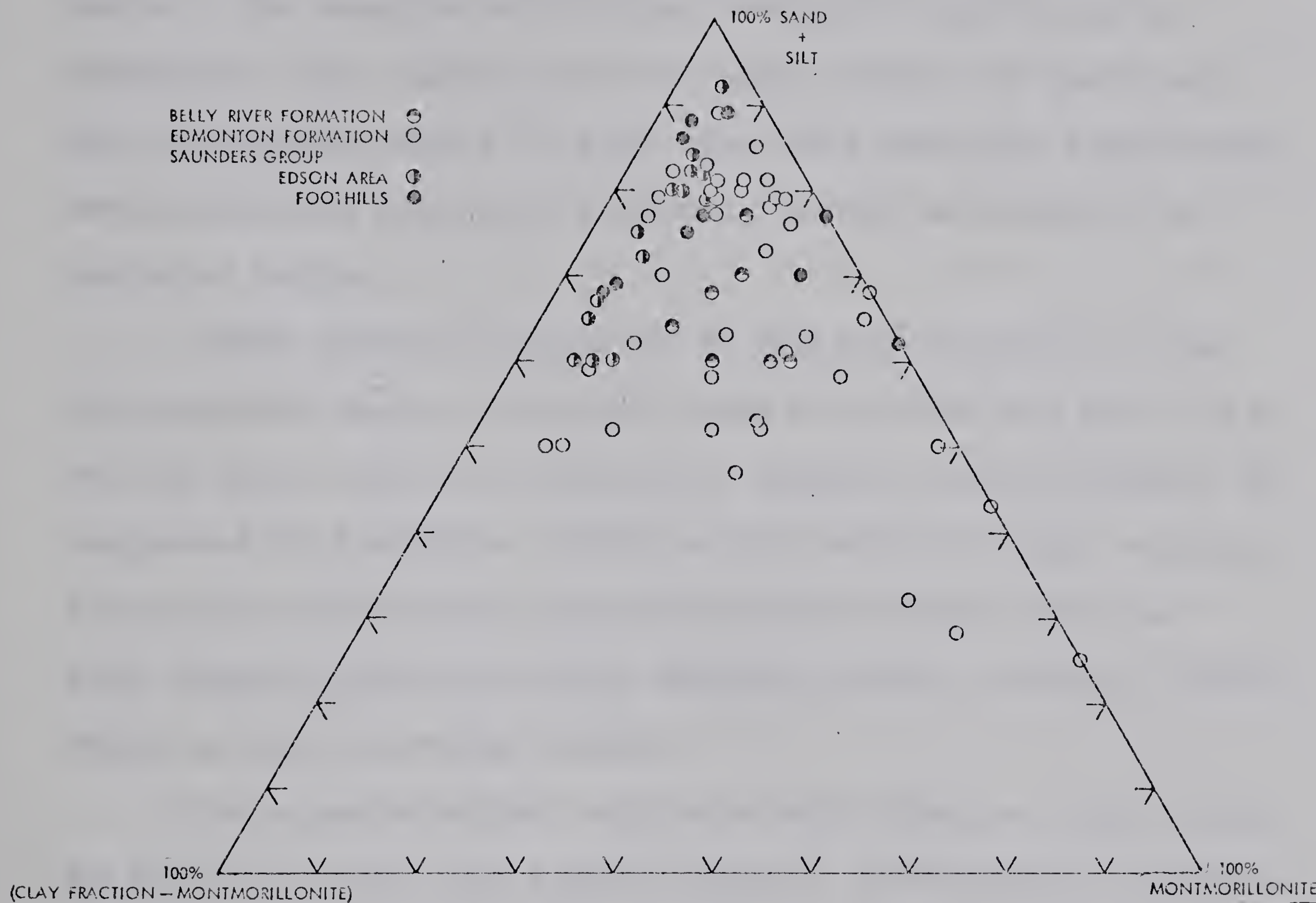
Of particular interest to the soils engineer is the clay fraction which is dominated by montmorillonite and illite. A study of the ternary diagrams, Figures 7 and 8 reveals that montmorillonite is more common in the eastern portion of the study area (Belly River and Edmonton Formation) than illite, which, together with chlorite, predominates in the clay mineral fraction to the west (Saunders Group). Montmorillonite accounts for an average of 23 per cent of the total rock composition with a range of 5 to 92 per cent in the eastern part of the area, whereas in the western portion the average montmorillonite content is 9 per cent with a range of 4 to 38 per cent. Illite accounts for 10 per cent of the total rock composition with a range of 0 to 30 per cent in the eastern part of the area, whereas in the western portion the average is 12 per cent with a range of 0 to 24 per cent. Kaolinite and chlorite are minor constituents with each contributing on the average to about 2 per cent of the total composition.

Organic matter is a common constituent in the fine-grained rocks of central Alberta, forming coal seams of considerable thickness and extent in parts of the area. However, in most samples it is present as scattered comminuted flakes and thin partings lying parallel to the bedding as shown in Plate 9,



TERNARY DIAGRAM OF THE PER CENTS MONTMORILLONITE, KAOLINITE, AND ILLITE PLUS CHLORITE IN THE CLAY FRACTION OF THE ALBERTA ROCKS

FIGURE 7



TERNARY DIAGRAM OF THE PER CENTS SAND PLUS SILT, MONTMORILLONITE, AND CLAY FRACTION MINUS MONTMORILLONITE IN THE ALBERTA ROCKS

FIGURE 8

Figure 1 and Plate 11, Figure 2. The appearance of the organic matter suggests that it has undergone considerable alteration, as much of it resembles coal or coal-like material when viewed either on a macroscopic or microscopic scale. For example Belly River Formation siltstones at Waskatenau (SRW series) exhibit small flakes of coal about one centimeter square in plan view, and numerous translucent, amber-coloured masses of isotropic matter believed to be resinous bodies.

There does not appear to be any relationship in the fine-grained rocks of central Alberta between the grain size of the sample and the quantity of organic matter present, as suggested by Pettijohn (1957) on the basis of other studies. Pettijohn states that clayey sediments contain twice as much organic matter as silty deposits which, in turn, contain twice as much as sandy strata.

The organic matter imparts a dark brown or black colour to the soft rock, thus highly organic claystone or siltstone may be readily recognized in outcrop.

Small amounts of pyrite exist in many samples, in particular, in those rocks which have a high proportion of organic matter. It is present as small flecks or irregularly-shaped growths up to about 3 mm. in size (note black bodies in Plate 12).

Calcite and siderite are the most common carbonates, with the former predominating. Siderite is generally found in association with ironstone beds. These carbonates, as detected both in thin sections and in chemical tests, are the only visible cementing agents in the fine-grained rocks of central Alberta. Where present these carbonate cements greatly enhance the strength of the rock. Carbonate distribution is erratic on both the microscopic (thin section) and macroscopic (outcrop) scale. In thin sections calcite cement is present as irregular patterns and patches (Plate 3, Figure 1 and 2) as well as "grains". In outcrop, hard carbonate cemented lenses are interbedded with soft uncemented or clay-cemented sandstones and siltstones (e.g. Edmonton Formation).

It is conceivable that many of the fine-grained rocks of central Alberta also contain substantial amounts of silica as a cementing material, although the problem of detecting it in thin sections appears to be insurmountable. A chemical analysis will reveal the proportion of silica present in a rock, but no distinction can be made between its existence as either detritus (e.g. a quartz particle) or as a cementing agent. The siltstone from Shiningbank Ridge (SR-1) is postulated to contain a silica cement, in light of its resistance to breakdown by freeze-thaw action and of the existence of a very high quartz peak on the X-ray diffraction pattern of the clay-sized material.

Soluble Salt Composition

Soluble salts present in clays or fine-grained rocks will affect the adsorbed ion complex and the electrolyte in the free water or pore water system . The types and concentrations of cations that make up the salt content depend, among other factors, on the salt content of the original depositional medium and subsequent ground waters. The influence of cation type and concentration on such properties as plasticity, strength, compression, etc. is well documented, e.g. Kenney, 1967; Grim, 1962; Mead, 1964; Thomson, 1963; Locker 1963.

Procedure

The total cation exchange capacity, and types and quantities of adsorbed cations, and the concentration of salts in the pore water were determined by the flame photometer and titration procedure[1]. With the flame photometer, a value for the total salt content was determined by finding the amounts of calcium, potassium, sodium, and magnesium present. The titration procedure provided a value for the cation exchange capacity. The concentration of salts in the pore water was taken as the difference between the cation

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[1] Determinations performed by the staff of the Geology Division Chemistry Laboratory, Research Council of Alberta.

exchange capacity and the total salt content. The error associated in the flame photometer determinations is in the order of 1 to 3 per cent; the titration error is not known but may be assumed to be approximately 4 to 6 per cent (Locker, 1963).

Unfortunately, the above procedures do not permit identification and quantitative evaluation of the cations that are either adsorbed or present in the pore water (i.e. the above procedures provide values for identification and quantitative evaluation for the total cation complex). To evaluate only the electrolyte, excessively high pressures, perhaps in the order of 3000 to 4000 p.s.i., would be required to expel the pore water for identification tests. Equipment to perform this expulsion is not presently available at the University of Alberta.

Results

The analyses reveal that calcium, sodium, and magnesium, in that order of abundance are commonly present as adsorbed ions or in the pore water of the fine-grained rocks of central Alberta. Potassium is found only in negligible quantities. Calcium is present in all rocks analysed with an average value of 37 m.e. per 100 gm. of air dried soil (a.d.s.) and a range of 12 to 100 m.e. per 100 gm. a.d.s. The sodium content is slightly higher in the eastern areas (Belly River and Edmonton Formation) where

it is associated with higher montmorillonite contents. Here the average sodium content is 11 m.e. per 100 gm. a.d.s. with a range of 1 to 67 m.e. per 100 gm. a.d.s., whereas in the western portion (Saunders Group) the average drops to 6 m.e. per 100 gm. a.d.s. with a range of 1 to 38 m.e. per 100 gm. a.d.s. Magnesium is present in quantities which on the average are comparable, but not associated with, the sodium content. With the information available only general comments with respect to salt content can be made, for the exchange cation does not appear to be consistent in its distribution with respect to geologic formation, rock type, or location. For example, the Leseur Slide area and the River Bank Stability site, which are only five miles apart and are both associated with the Edmonton Formation, have bentonitic claystones present at depth which have entirely different exchangeable cation complexes (LA and RB series of samples).

It is of interest to note that in some sample series (AGT, W), the sodium ion content tends to increase with depth (Table III, column 9). This situation may indicate either a decrease in the salinity of the original depositional enviroment with time, a leaching out of the salts from upper strata and redeposition in successively lower strata, or the result of a combination of these two factors.

Structures

Structures of sedimentary rocks are textural or compositional inhomogeneities usually visible at the hand specimen or megascopic level. They can be classed as:

(1) primary (or depositional)

(2) secondary (or postdepositional) — early diagenetic / late diagenetic

Primary structures are those produced during deposition, such as bedding, laminations and various types of ripple structures. Secondary structures are produced by organisms, physico-chemical agencies, or tectonic forces after deposition and can be classified into two groups. Early diagenetic structures are formed while the sediment is still in a soft state; examples are slump structures, burrow structures, and various types of nodules. Late diagenetic or induced structures are those formed by tectonic or "rebound" processes and include various types of faulting and fissuring.

Primary Structures

Of particular interest to the engineer are various types of physical discontinuities in siltstones and claystones, especially laminations and fissures. Laminations, which are bedding units less than one centimetre thick, appear to be of two main types in fine-grained rocks:

(1) alternations of course and fine particles (silt and clay);

(2) alternations of material of different composition, such as quartz and organic debris, calcium carbonate and quartz silt, etc.

These laminations are probably due to differential settling rates of the various constituents associated with local fluctuations in conditions of deposition. Some may be associated with a yearly climatic cycle in the same way as varved clays (Pettijohn, 1957), although in actual fact, the absence of laminations is more remarkable than the laminations themselves because only the existence of very uniform sedimentation over a long time will produce a structureless sediment.

Primary structures in the fine-grained rocks of central Alberta are reported in Table IV, columns 6 to 8. Laminations, which are found in the majority of the materials studied, are reported as either faint or strong, depending on their definition. In most of the rocks the laminated structure is defined by the presence or absence of organic matter, which if present imparts a dark colour, e.g. Plate 5, Figure 1. The individual particles or lenses of organic material are generally oriented parallel to the bedding, but may cut across it in some cases, e.g. Plate 11, Figure 2. It may be reasoned that the smaller particles of organic matter settle out in conjunction with the detrital grains and align them-

selves parallel to the bedding surfaces during deposition or compression, whereas longer lenses or "partings" of organic matter, which originally may have been short tree branches or plant fronds have settled in a random fashion and resisted realignment during compression. Hence, these materials cut across the apparent bedding planes of some rocks.

Laminations which are developed by alternations of calcium carbonate and silt also are present in a few samples but are not clearly defined. In such cases carbonates are present as subovoid patches composed of finely crystalline "concretionary" material (Plate 3, Figure 1), as irregularly concentrated, optically continuous patches filling intergranular areas (Plate 3, Figure 2), or as disseminated patches of cement. Whether or not the distribution of carbonate structures constitutes a "laminated" structure depends upon the scale of study, i.e. a lenticular patch of carbonate-cemented material may appear as a laminated structure in hand specimen but irregular if viewed in thin section.

Laminations which are developed by variations in grain size (Plate 8, Figure 1) or in conjunction with variation in organic content are present in numerous samples; such laminations may be explained by quite local fluctuations in the influx of sediment-laden waters due to storms and seasonal variations.

A particularly interesting type of lamination is that developed by the presence of thin seams of montmorillonite.

For example, the specimen in Plate 11, Figure 1, shows a one millimetre-thick seam of well-oriented montmorillonite parallel to the bedding but with a neck or plug extending down from the base of the seam into the underlying material. The vertical neck of this seam appears to be an infilling of montmorillonite into what may have been a burrow structure or dessication crack. The latter structure requires the following sequence of events: a subaerial plane of freshly deposited sedimentary material, drying and cracking of this surface, and finally the filling of the cracks by volcanic ash deposited subaerially or subaqueously. Montmorillonite also is present in concentrated pockets (Plate 2, Figure 1), disseminated throughout the mass, Plate 4, Figure 2, or in semi-concentrated layers or beds (Plate 2, Figure 2) called "bentonite" on a megascopic scale.

Pellets, which appear as small, rounded aggregates of clay, often highly oriented, impart a primary structure to a number of samples (Plate 10, Figure 1). Pellet formation has been attributed to the action of water currents (Pettijohn, 1957), and although the clay fraction in the pellets themselves is generally oriented, the large size and irregular shape supports a local origin. That is, they probably have been derived from the breakup and redeposition of nearby clayey sediments, temporarily exposed to drying and hardening, with a minimum of abrasion and sorting.

"Brecciated" structures, as illustrated in Plate 10, Figure 2, are composed of angular (brecciated) fragments of clay-sized material which can be distinguished from the surrounding clay matrix by differences in shape and texture such as a distinct change in the degree of direction of preferred orientation of the enclosed clay particles as compared to that of the clay matrix. These materials are susceptible to cracking at the fragment borders, as illustrated in Plate 10 and when subjected to wet-dry cycles show a preference for the matrix to break up first and the fragments later.

The origin of some of these fragments is debatable but the following mechanisms may be considered:

(1) large fragments of volcanic debris or glass were carried to the depositional area by rivers and subsequently altered. However the strong orientation of the clay minerals in the breccia fragments refutes this hypothesis, for in other samples composed of altered volcanic glass with remnant shard texture, the clay matrix is not oriented.

(2) the fragments may be "shale" detritus from the original source area to the west but a relatively soft rock of this nature would not retain its angularity or inordinately large size during transport.

(3) a more realistic hypothesis attributes the original of the brecciated fragments to the dessication of subaerial plains of freshly deposited sediments to

form irregular, angular fragments which, in turn, were reworked and buried by later influxes of fine sediment. Dessication must have been severe enough to impart sufficient strength to the fragments to allow them to maintain their angularity during the relatively short reworking process. With increased amount of transportation and erosion, such fragments grade into rounded pellets.

Homogeneous, i.e. structureless rocks are present, at least as observed within the areal extent of the thin sections (approximately 3/4 x 1.0 inches), although the bulk of the specimens show some evidence of primary structures.

Secondary Structures - Early Diagenetic Types

Secondary structures believed to have developed in the early stages of diagenesis in the fine-grained rocks of central Alberta include slump features and ironstone nodules.

Slump structures are found in several samples, an example of which is shown in Plate 12, Figure 1. The slumping and rotation of the small blocks is emphasized by the relative displacements of laminated organic matter (dark coloured). It is of interest to note that this slump feature is comparable in character to the massive slumping which occurs along the river valley walls in the Edmonton Formation,

in the eastern part of the study area, i.e. it is a block movement leaving a relatively steep scarp and sliding on a horizontal lower boundary. The microscopic fault planes are infilled with material of a grain size distribution comparable to that of the ambient material; a flow texture comparable to that described by Carozzi (1960) is found in these cracks. The silt particles are aligned parallel to the walls of the crack and when the structure is viewed under crossed nicols the clay matrix also appears to follow this pattern. Slump structures and flow textures may be considered to characterize sedimentary deposits that have been submitted to alternating periods of dehydration and wetting.

"Swirly" structures (Plate 2, Figure 2) also may be a form of flow structure. The swirly arrangement of montmorillonite aggregates is no doubt due to slight flow of freshly deposited montmorillonite.

Iron-bearing concretions (ironstone nodules) which appear as pellet structures in thin sections are commonly found in the soft rocks of central Alberta. They range in size from fractions of an inch to a foot in diameter and may be found collectively in bands referred to as clay ironstone beds. They are believed to be composed of segregations of iron minerals (mainly siderite and iron oxides such as goethite) and clay minerals, which formed during or shortly after deposition as a product of diagenesis. (Krumbein and Sloss, 1951; Carozzi, 1960).

Secondary Structures - Late Diagenetic Types

Fissility

Fissility, which is the ability of rocks to split into sheets along certain preferred planes (usually parallel to bedding planes), is a structural feature that forms one of the bases for the classification of fine-grained, clayey rocks. It has been attributed to the parallel orientation of the platy constituents of the rocks (micas, clay minerals, organic matter), accentuated by compaction and possibly concomitant recrystallization (Pettijohn, 1957). Thus, although a tendency towards fissility is inherent in certain rocks (especially laminated ones) from the outset, the property usually is best developed during the later stages of diagenesis, becoming quite noticeable in partly recrystallized rocks of metamorphic origin (slates, schists).

Ingram (1953) recognized three major groups of breaking characteristics in fine-grained sedimentary rocks: massive, flaggy, and flaky. He also noted the following features with respect to fissility:

(a) fissility is associated with parallel arrangement (orientation) of clay particles

(b) fissility increases with an increase in organic matter

(c) cementing agents decrease fissility

(d) weathering increases the fissility of shale by the removal of cementing agents and by the expansion of clay particles.

Well-developed fissility is uncommon in the fine-grained rocks of central Alberta most of which can be classified as siltstones or claystones. A crude form of fissility may be observed in certain lithologic units in outcrops, but weathering of soft rocks is known to produce this phenomena (Ingram, 1953). Fissility, as formed by weathering should be considered an induced property of the rocks and not an inherent characteristic of the material for classification purposes. The lack of abundant well-oriented clay minerals plus the presence of carbonate cement no doubt contributes to the paucity of fissility. The minor amounts of fissility present, in particular that which developes in outcrop, is believed to be a manifestation of the laminated organic matter.

Physical Discontinuities

Associated with fissility in fine-grained sedimentary rocks are various types of physical discontinuities that manifest themselves as cracks or gaps or potential gaps in the rock framework. Some of the more common types of physical discontinuities are classified in Table VI, together with the presumed causes and effects. Bedding and fissility surfaces are listed as potential rather than actual breaks, often serving as the loci for fractures developed during diagenesis

TABLE VI

TYPES OF PHYSICAL DISCONTINUITIES IN FINE-GRAINED SEDIMENTARY ROCK

Type	Structure	Attitude	Major Causes
Primary (during sedimentation)	Bedding planes	Parallel to depositional surface	Variations in competence of transporting agents; variations in sediment type supplied.
Secondary (during diagenesis)	Fissility Surfaces	Generally parallel to bedding	Parallel orientation of platy particles; presence of organic matter.
	Syneresis cracks	Random	Shrinking and swelling of colloidal matter,
	Fissures	Variable	Tectonic forces; dessication; rebound; weathering.
	Faults and joints	Variable	Tectonic forces

by tectonic forces.

Fissuring, in general, refers to the network of small, hairline cracks developed in many partially indurated claystones and siltstones. These cracks may be microscopic or macroscopic, dividing the soil mass into roughly equidimensional fragments from a few feet to a fraction of an inch in dimension.

Fissures may develop along planes of weakness in a soil or soft rock mass subjected to rebound. Because rebound occurs perpendicular to the plane of the distributed load which was removed, fissures may develop parallel to a planar surface in a level area or parallel to valley walls where material has been removed, e.g. by a degrading river. However, the stresses which develop the fissures seldom will be uniformly distributed throughout the mass. Complex mineralogy results in nonuniform swelling which, in turn, produces differential movement. Also, poorly bonded regions will succumb to rebound stresses quicker than strongly bonded areas; consequently, nonuniform stress conditions will develop. Unequal stress concentrations, in turn, lead to nonuniform deformation, and random fissuring results. Thus, the direction of fissure planes will follow the direction of load removal in a general manner, although to some extent modified by the inherent characteristics of the mass.

In conjunction with the development of fissures by rebound, the destructive powers of weathering contribute to

fissuring. Variations in water content and temperature subject the soft rock to wet-dry cycles (shrinkage and expansion) and freeze-thaw cycles. Both of these actions cause displacement and ultimately fissuring in near-surface materials. The visual effect of weathering is often marked by discoloration of material adjacent to the fissures, which may be attributed to slight mineralogical changes such as alteration of cementing agents. The depths to which weathering affects the material may be limited to 30 to 40 feet, whereas fissuring due to rebound may extend to depths of a hundred feet or more.

All of the fine-grained rocks examined during the course of the study exhibit complex fissure patterns in outcrop. In addition, the rocks of the Foothills region exhibit large-scale faulting and widespread jointing, which features are outside the scope of this investigation.

Detailed studies of fissure orientation were not made in the field, but it was noted that the degree of fissuring decreases in an east-to-west direction, as indicated by an increase in "fragment" size toward the west. In fact, in the eastern portion of the study area much of the near-surface mass exposed in outcrop has either reverted to a soil or is very close to this condition. The fine-grained rock recovered from coreholes also exhibits considerable fissuring up to depths of 10 to 20 feet below the upper surface of the bedrock. These fissures are generally badly stained by iron oxides which indicates that some weathering of these rocks has

occurred either before or after Pleistocene glaciation.

Fissures or cracks noted in thin sections are considered as artifically induced structures because most appear to have developed during thin section preparation. However these cracks may reflect planes of inherent weakness within the sample, i.e. they form along inherent potential fissure planes of the rock. The distribution of these cracks is presented in Table IV, columns 10 and 11, along with information on their attitude and degree of staining. About 75 per cent of cracks are parallel to the bedding which fact indicates that the presence of laminated clayey and organic matter constitute planes of weakness that control fissuring (Plate 8, Figure 1). Many of the cracks have developed in laminations with a high clay content, in particular seams of montmorillonite (Plate 11, Figure 2; Plate 9, Figure 2). Very few cracks occur within laminations of high silt content or in a direction perpendicular to the bedding. The presence of staining (believed to be due to iron oxides) adjacent to about one-third of the cracks indicates that these cracks, at least, existed <u>in situ</u> as microfissures. Fissuring therefore, is a common form of discontinuity in the fine-grained rocks of central Alberta on both a macroscopic and microscopic scale.

In contrast to the more regular fissure patterns found in laminated rocks, the brecciated and shard-textured rocks exhibit random cracking. The cracks are found throughout the

"matrix" of the rocks, but extend around the shards or breccia fragments which indicates that these features have a higher intrinsic strength. Random cracking patterns develop blocky or nugget-type fragments which may be observed in the field or as the product of wet-dry cycle testing in the laboratory. In thin sections some clay aggregates, normally montmorillonitic, are observed to be arranged to form a "swirly" structure (Plate 2, Figure 2); these materials are susceptible to breaking down into nuggets in a fashion comparable to the exfoliation of a granite.

A peculiar form of cracking found in concentrated pockets of montmorillonite (Plate 2, Figure 1) is attributed to syneresis. Syneresis is a colloidal process whereby the particles draw themselves together under the action of attractive forces and expell some of the pore water; this process may be responsible for fissures in London clay (Skempton and Northey, 1952). These concentrated pockets of montmorillonite probably were colloidal gels during the earlier stages of formation. The concentric ring pattern illustrated in Plate 2 corresponds to the rearrangement and adjustment of the colloidal particles during wetting and drying cycles of the fresh deposit, i.e. syneresis cycles.

In summary, widespread fissuring in the near-surface fine-grained bedrock of central Alberta is in part a result of stress release (rebound) which occured in conjunction with and following the erosion of up to 2000 feet of Tertiary

sediments (Rutherford, 1928). The stress cycle (or perhaps cycles) imposed by the advance and retreat of thick ice sheets during Pleistocene also affected the development of near-surface fissures. The susceptibility of montmorillonite to extensive volume change (shrinking and swelling) likely established conditions of nonuniform stress distribution that led to the development of fissures. In addition, other processes during geologic history such as the periglacial climate of the Pleistocene may have contributed to the present highly-fissured nature of the fine-grained rocks.

Plasticity

Plasticity, which is defined as the ability of a material to deform under stress without rupture, may be expressed by quantitative parameters, i.e. Atterberg limits. The plasticity characteristics of soils are used for classification and identification purposes as well as indicies of soil behavior.

The plasticity characteristics of a soft rock may vary widely in accordance with:

(1) the clay mineral type;

(2) the percentages of clay mineral type present;

(3) the type and concentration of adsorbed cations;

(4) the type and concentration of cations in the pore water.

The influence of these factors on plasticity is well documented in the literature, e.g. Grim, 1962; Seed et al, 1967. The degree of influence of these factors is variable but the highest plasticity values are found in clays composed of pure montmorillonite with a sodium adsorbed ion complex and zero salts in the pore water. Many soft rocks of the Great Plains region of North America exhibit high plasticity characteristics, for they contain substantial quantities of naturally occurring rock type of comparable composition and chemistry, bentonite.

The liquid limits and plastic limits were performed in accordance with A.S.T.M. designations D423-61T and D424-59 respectively, with the following exceptions:

(1) the soil was not air-dried but rather broken down from the natural water content by a freeze-thaw procedure (samples received in air-dried state were subjected to the same treatment);

(2) alterations in the water content required to change the consistency of the soil for liquid limit determinations were allowed to come to equilibrium for a minimum period of 24 hours.

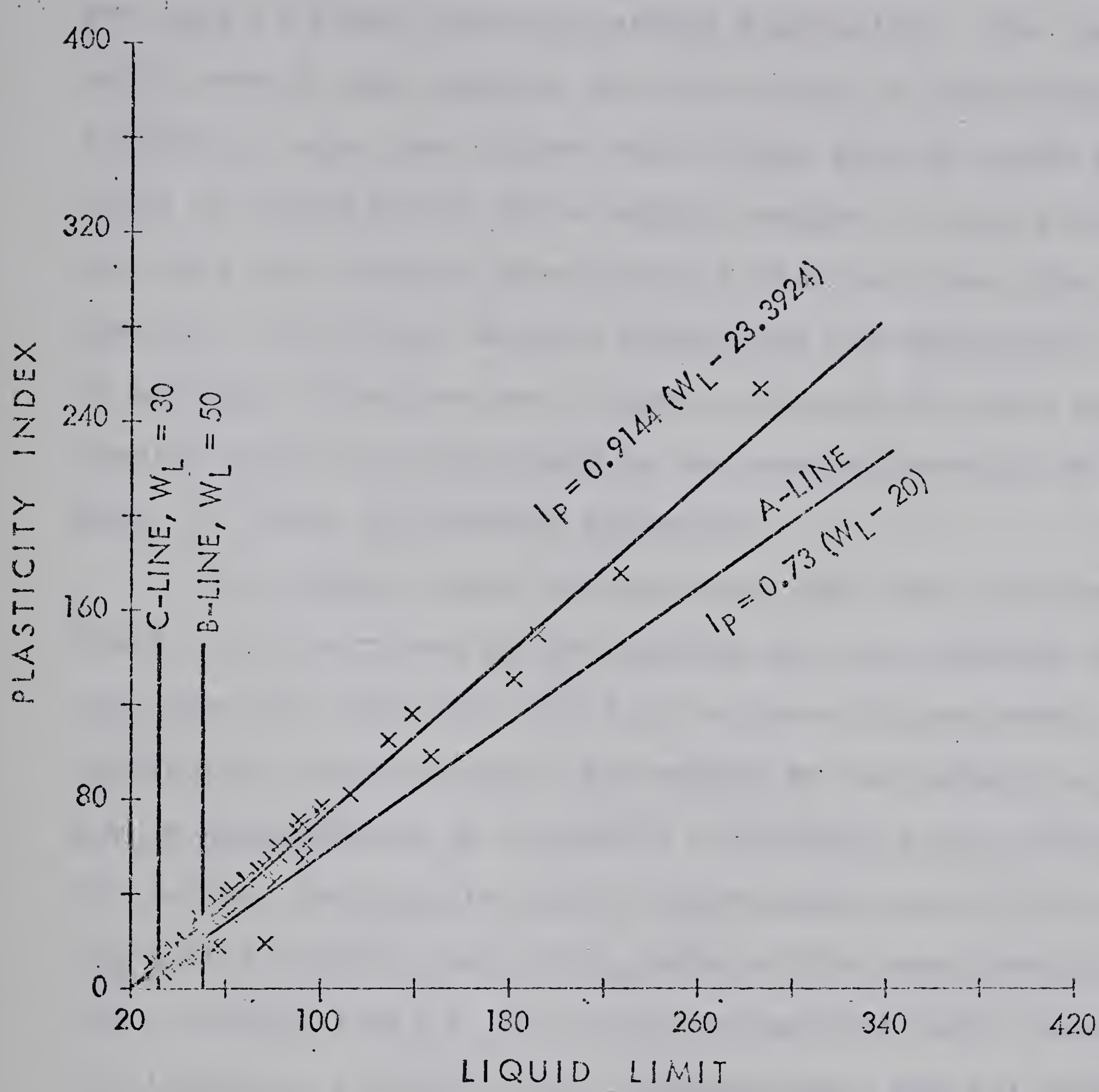
(3) the Casagrande grooving tool was used in the liquid limit test.

Air or oven-drying of soils will generally cause a decrease in the liquid limit of a soil because of either irreversible aggregation of colloidal material or irrever-

sible dehydration of organic matter (Yong and Warkentin, 1966). As the fine-grained rocks described here were broken down from natural water content by freeze-thaw cycles, the liquid limits should be representative of the natural state and should not suffer from inconsistencies.

Results

All the fine-grained rocks from central Alberta exhibit plasticity except those from Lower Cretaceous beds at Cadomin and a highly organic sample (MRH-1) from the Foothills region near Hinton. The range of plasticity values is high, as might be expected from rocks with such a wide variation in clay content and mineralogy (sandy siltstones to bentonite). A study of the data in Table III and the plasticity chart (Figure 9) indicates that 53 per cent of the samples can be classed as inorganic clays of high plasticity, 26 per cent as inorganic clays of medium plasticity, 14 per cent as organic or inorganic silts and silty-clays of medium plasticity, and 6 per cent as organic clay and silts. The very low number of "organic" rocks seems to conflict with the abundance of organic matter reported in them. However, the organic material in the soft rocks of central Alberta has undergone considerable alteration to an inactive coal-like substance



PLASTICITY CHART FOR THE ALBERTA ROCKS

FIGURE 9

and thus it likely does not affect plasticity. The important point here is that despite the wide range in plasticity characteristics, more than 80 per cent of the Alberta rocks are composed of constituents which exhibit medium to high plasticity and that some samples have liquid limits well over 200. No specific correlation between plasticity and geographic location or geologic formation can be made, although the most highly plastic materials were found in the eastern portion of the study area, in rocks of Edmonton Formation.

The natural water contents are less than the plastic limits in 98 per cent of the samples and are believed to be less than the shrinkage limit in at least 90 per cent. (Shrinkage limits were not determined by laboratory tests but may be approximated by extending a straight line, parallel to the A-line, through the point representing the soil on the plasticity chart to cut the W_L-axis at the water content of the shrinkage limit.) With such low natural water contents, the liquidity indicies, with one exception, are all negative and drop to values as low as - 2.58.

The Atterberg limits and their associated indicies for the fine-grained rocks of central Alberta are reported in Table III, columns 16 to 20. The values for the "activity" index were determined by dividing the plasticity index by the per cent clay-sized materials as proposed by Skempton (1953).

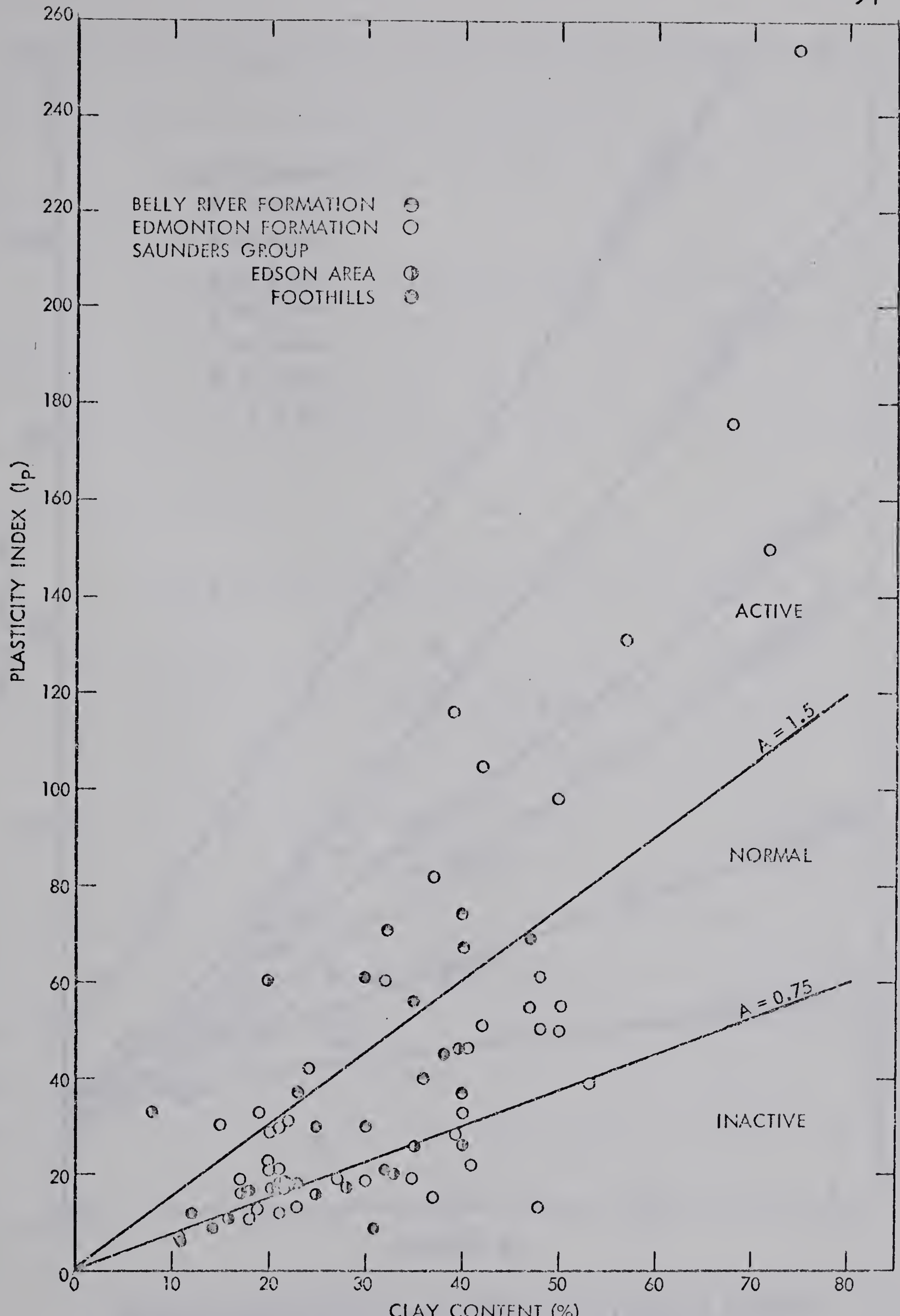
The relationship between liquid limit and plasticity index is plotted on the plasticity chart in Figure 9, which

was devised by Casagrande (1948) on the basis of the analysis of plasticity characteristics of many soil types of different geological origins and mineral compositions. Casagrande (1948) showed that soils having a common geological origin plotted along a line parallel with the empirically derived A-line defined by the equation, $I_p = 0.73\ (W_L-20)$. The "best fit" line for the relationship between the liquid limit and the plasticity index for the fine-grained rocks of central Alberta is defined by the equation, $I_p = 0.9144\ (W_L-23.3924)$ which is not parallel to the A-line. This deviation may be attributed to differences in the "origin" of the mineral constituents of the rocks despite the fact that they have a common geographical source of sediments which were deposited in a common depositional enviroment (nonmarine). That is, the clastic constituents (e.g. quartz, feldspars, micas) are erosional products from similar parent rocks, but the associated clay minerals have been in large part derived from post-depositional alteration of volcanic detritus. In addition the clay content has undergone the later effects of diagenesis, most noticeable in the Foothills where much of the montmorillonite content may have altered to illite and chlorite.(Carrigy and Mellon, 1964). Thus, the best fit line on the plasticity chart would not be expected to fall parallel to the A-line as suggested by Casagrande's theory (1948).

Plots of plasticity index versus clay content for a specific soil type produce a straight line which extrapolates

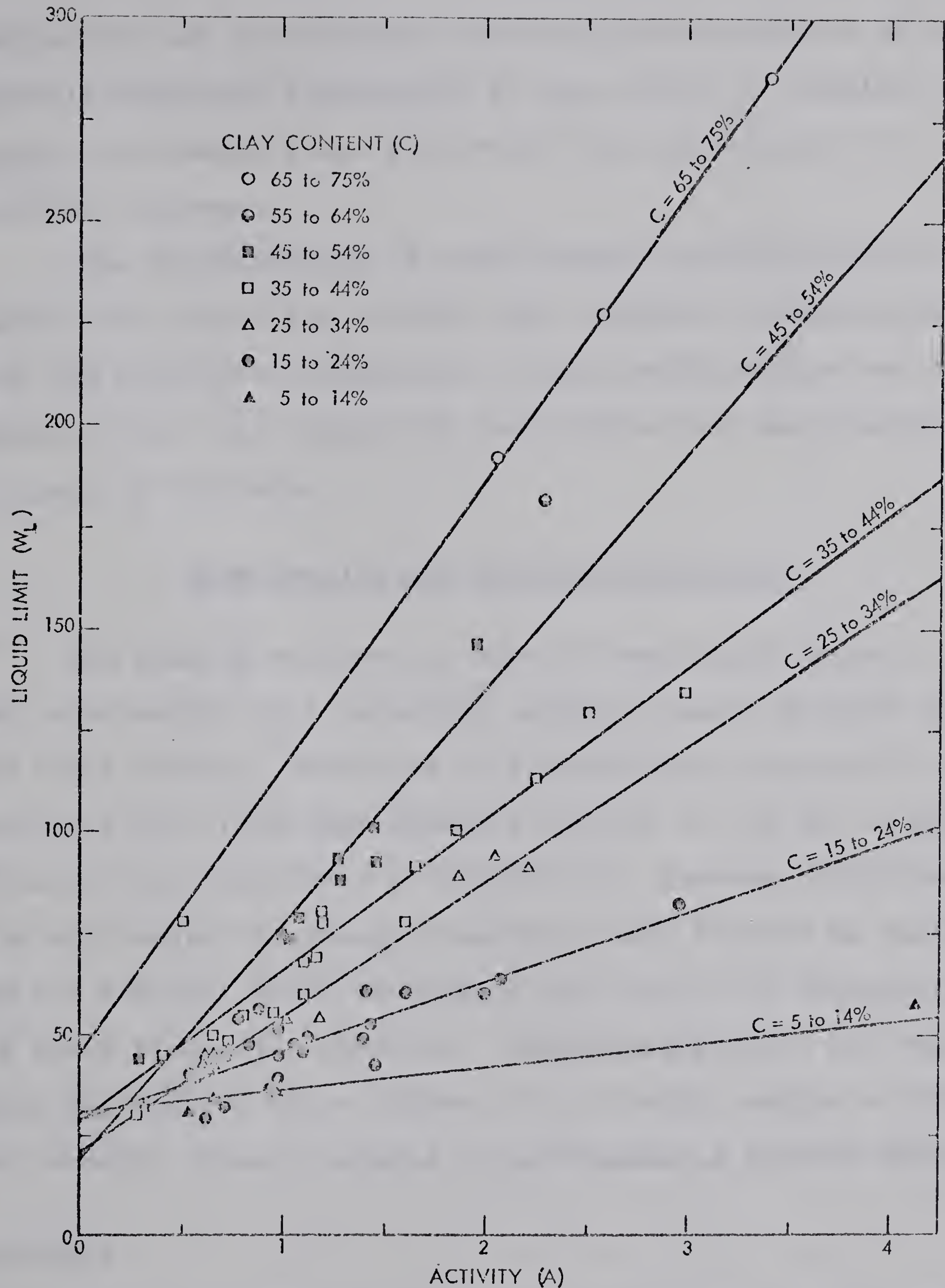
back through the origin (Skempton, 1953). In a similar plot (Figure 10) the fine-grained rocks from central Alberta show a wide scatter of points through which a number of straight lines pass through the origin could be drawn, each of which would represent a specific activity. This diagram emphasizes the variations in mineralogical composition and the associated ion complexes that exist in these rocks, which fall in approximately equal numbers into three broad groups - active, normal, and inactive - based on criteria devised by Skempton (1953). The majority of samples from the eastern part of the area (Belly River, Edmonton, and Paskapoo Formations) are normal to active rocks, whereas most from the western part of the area including the Foothills, are inactive to normal rocks.

Seed et al (1964 a) presented plots illustrating many interesting plasticity relationships; among which is a plot of liquid limit versus activity for different fabricated soil types with variable clay contents. They noted that for any specific clay content, a unique relationship exists between activity and liquid limit regardless of the proportions of the clay minerals, present (montmorillonite, illite, and kaolinite). A similar relationship exists for the fine-grained soft rocks of central Alberta (Figure 11), although it was necessary to accept a range of clay contents for each curve due to the extreme variability in the clay content of the samples. The degree of scatter is acceptable in view of the fact that the



RELATIONSHIPS OF PLASTICITY INDICES TO CLAY CONTENTS
TO ILLUSTRATE ACTIVITIES OF ALBERTA ROCKS

FIGURE 10



RELATIONSHIPS OF ACTIVITIES TO LIQUID LIMITS
FOR RANGES OF CLAY CONTENTS

FIGURE 11

samples are not pure systems but are natural mixtures of many minerals which are susceptible to the effects of physico-chemical phenomena (e.g. electrolyte concentrations) to different degrees.

The distributions of clay content, montmorillonite content and sodium ion content show excellent correlations with the plasticity parameters. These relationships are discussed in the next chapter in conjunction with multivarient analysis of the data.

Bulk Density and Related Properties

The density referred to here is total unit weight, i.e. the total weight of a naturally occuring sample divided by its total volume. Densities of fine-grained sedimentary rocks generally vary from approximately 105 pcf to 170 pcf in accordance with the degree of induration. However, densities also are subject to changes caused by such factors as weathering and rebound, which counteract the effects of compression and other diagenetic agencies. Related properties are void ratio and natural water content of the rocks, values of which are normally closely related to corresponding density values.

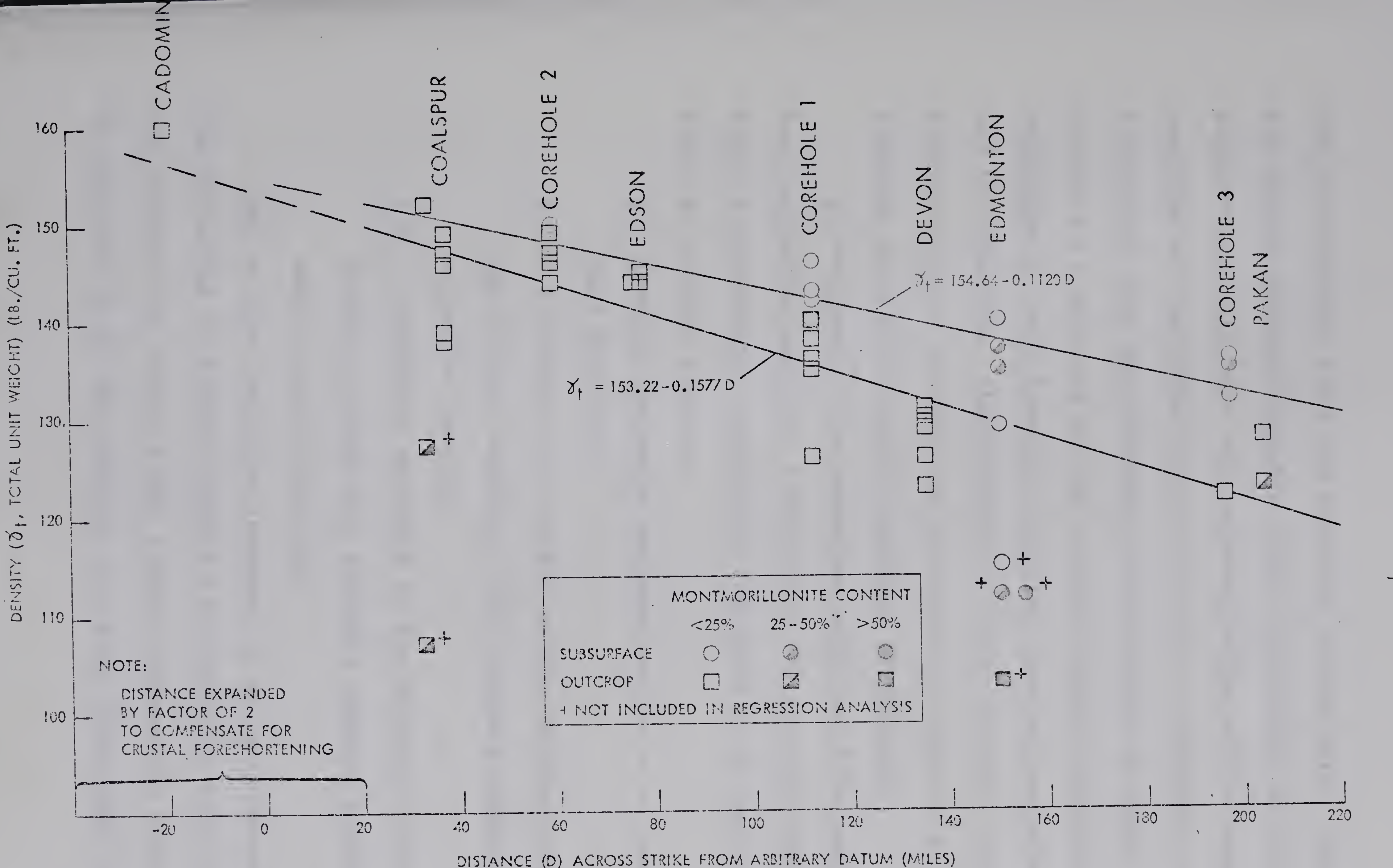
Procedure

Density was determined by the direct measurement of a sample's weight, with the corresponding volume being found by mercury immersion. Three portions of the same sample

were determined to provide an average density value. Air-dried samples were not measured.

Results

The results of density, water content, and void ratio measurements are given in Table III, columns 21 to 23. The three properties are highly correlated (Table VIII) and it is obvious that both water content and void ratio can be predicted from measurements of bulk density alone. The fine-grained rocks of central Alberta exhibit wide variation in bulk density values, ranging from 103 pcf for a bentonite from the Edmonton Formation (RB-2) to 160 pcf for "shale" from the Lower Cretaceous beds at Cadomin (Figure 1). In general there appears to be a systematic increase in bulk density from east to west across the study area as indicated in Figure 12 where bulk density values are plotted against projected distance across the strike of the beds from an arbitrary datum. Two linear regression lines are illustrated in Figure 12: one for corehole samples and another for outcrop samples. The distance for each sample location have been projected and measured with respect to a line that is perpendicular to the strike of the folded belt of the Rocky Mountain Foothills, with an arbitrarily chosen origin 20 miles west of Cadomin (Figure 1). Each sample also is classified according to the gross amount of montmorillonite present. Six samples not included in the regression analysis (marked by +) were excluded because they



BULK DENSITY vs. DISTANCE FOR OUTCROP AND COREHOLE SAMPLES FOR THE ALBERTA ROCKS

FIGURE 12

are inconsistent with the majority of the data. Five of these are highly montmorillonitic rocks (bentonites or bentonitic claystones) which are not representative of the average composition of the rocks but are plotted to illustrate that wide deviations from the proposed relationships do occur. That is, distance is only one of the several factors associated with variation in rock density; therefore perfect correlation cannot be expected. Significance of other factors, including montmorillonite content, is discussed in Chapter VI in conjunction with multivariate analysis of the data.

If the bentonitic rocks are excluded from consideration, the regression analysis (Figure 12) illustrates three distinct relationships concerning the density of the fine-grained rocks of central Alberta.

(1) density increases systematically in an east- to west direction;

(2) a difference in density exists between corehole and outcrop samples, with corehole samples having a greater density;

(3) a systematic decrease in the density difference between outcrop and corehole samples exists in an east-to-west direction.

Why do the densities increase in an east-to-west direction? The variation in density cannot be correlated with geologic age because the oldest rocks (Upper Cretaceous) which might be expected to be the densest, are less dense than the younger

rocks (Tertiary) to the west. The geologic history of the strata provides a possible explanation (Figure 4).

By the end of the early Tertiary time, a wedge-shaped deposit of sediments which thickens towards the west had been built. The geologic processes then reversed and subsequent uplift and erosion stripped off hundreds of feet of these sediments. However, since the tectonic activity which brought about uplift was centered in what is now the Rocky Mountains, it is likely that uplift and, consequently, erosion was the greatest in the west. Thus, beds which are at or near the surface today were once buried under successively greater amounts of sediments in a westerly direction towards the Foothills. Since density is related to overburden, it follows that the densities should increase in a similar fashion regardless of the age of the rocks.

The effects of glaciation on density are difficult to assess, if only because the actual ice loads which existed and the distribution of these loads are unknown. The effects of the loads imposed by the thick ice sheets depend upon the degree of induration of the rock mass at the time of glaciation. It is reasonable to assume that the rocks attained (or near attained) their present indurated state prior to glaciation. Hence the least dense (or indurated) rocks in the eastern part of the study area (Edmonton and Belly River Formations) would be more likely to exhibit the effects of glaciation. Locally (Edmonton area), this is the case, where bedrock

been gouged or contorted due to ice action, but there is little evidence to show to what depths such obvious effects persist or whether any systematic variation in the distribution of these effects exists. In summary, the permanent effects of glaciation and subsequent deglaciation on the physical properties (e.g. bulk density) of the near-surface Cretaceous-Tertiary bedrock formations are largely unknown.

In addition to the postulated effects of depths of burial and glaciation on the density of bedrock formations of central Alberta, the effects of "tectonic" forces must be considered. That these effects played a significant role in bringing the rocks to their present state of induration is suggested by the density of the sample taken from Shiningback Ridge (SR-1), north of Edson (Figure 1). The density of this sample is comparable to that of the samples from Entwistle (P-series) on the Pembina River. Both of these locations are at equal distances (across the strike of the rocks) from the Foothills, but because Shiningback Ridge is an erosional remnant 1500 to 2000 feet above the general plains level, the sample (SR-1) should have a much lower density, if depth of burial is a major contributing factor. However, the rocks of central Alberta have been subjected to enormous horizontal compressive forces resulting from the tectonic activity which built the highly folded and faulted strata of the Rocky Mountains. It is probable that the effects of these same forces extended into the apparently undisturbed strata of the adjacent Plains,

although with diminishing degrees in an easterly direction, with the result that density (or degree of induration) increases as the Foothills are approached. The similarity of the rock densities at Shiningback Ridge and Entwistle, separated by about 1500 feet in elevation suggests that these compressive forces were a major contributing factor to the variation in density in the rocks of central Alberta.

The effect of horizontal compressive forces on density also is illustrated by the position on the density-distance plot (Figure 12) of the densities of the samples from Cadomin. It was assumed that the crust in this area has been foreshortened by a factor of two by compressive forces and the density has been plotted on an expanded scale. The proximity of the density to the regression line illustrates that this assumption is in the right order of magnitude and suggests that, indeed, compressive forces have markedly influenced the physical properties of the rocks.

The effects of rebound, associated with the stripping of overburden during middle Tertiary to Recent times on density are difficult to assess. The amount of rebound in the rocks depends, among other factors, upon the amount of overburden removed, the composition of the rocks and the bond strengths between the particles of the mass. The amount of montmorillonite in the rocks, which is known to augment rebound, shows a tendency to increase towards the east. An increase in bond strength associated with diagenesis and which will hinder rebound, occurs

towards the west. These two factors would contribute to greater rebound, hence lower densities, towards the east. However, the amount of overburden removed, associated with a greater degree of rebound, is thought to have increased in a westerly direction, thereby counteracting the effects of composition and diagenesis. Because of the complexity of these interactions, the effect of rebound on density is uncertain.

The density of outcrop samples should be lower than drill hole samples because weathering action decreases the density by the destruction of bonds and the associated uptake of water (Varnes, 1950). For example, sample P-33, which was selected from the top of the bedrock at the Entwistle corehole (Figure 1), has a density similar to outcrop samples from the same locality (Table III, column 21). This sample decreased in density by weathering action after Tertiary erosion and previous to glaciation.

The marked systematic decrease in the difference of corehole and outcrop sample density, as the study area is traversed from east-to-west, is synonymous with a greater resistance to weathering exhibited by the fine-grained rocks in this direction. This increased resistance to weathering is mainly attributed to (a) the composition of the rocks, e.g., montmorillonite, a material susceptible to weathering, tends to decrease towards the west and (b) to the increase of bond strength in a westward direction, as indicated by

the wet-dry cycle tests (Table III, column 26). (The danger of extrapolating the regression beyond the data, i.e. beyond the depositional basin should be noted.)

Related Properties

The natural water contents of the soft rocks of central Alberta generally range from 7 to 28 per cent but values of up to 62 per cent are found for the bentonites and highly bentonitic claystones (Table III column 23). If it is assumed that the rocks are saturated and the specific gravity is constant (it actually varies within relatively narrow limits) then the water content, the void ratio and the density are interdependent, i.e. if the water content increases, density decreases and void ratio increases, as shown by the regression analyses (Table VIII). Hence, the discussion related to density is indirectly applicable to water content variation. For example, a measure of the change in water content from drill hole to outcrop sample reflects the change in density or conversely, the effects of weathering.

Wet-Dry Cycle Tests

The reaction of fine-grained rocks to alternating cycles of wetting and drying can be used to evaluate the following interrelated properties:

(1) the degree of interparticle bonding, at least in a relative sense (Terzaghi and Peck, 1967);

(2) susceptibility to weathering (Philbrick, 1950);

(3) the distinction between "compacted" and "cemented" rocks (Philbrick, 1950);

(4) the relationship between bond strength and energy.

Test Procedure

Chunks of intact rock, approximately 1 to 2 inches in size, as obtained from outcrops and coreholes, were used without preparation. Attempts to cut the samples to cubes proved futile because of uncontrollable breakage. Initially the samples were immersed in distilled water for a period of up to 64 days to allow slaking. If the chunks disintegrated into soil particles during this period, the time required was noted; otherwise, the samples were subjected to alternate cycles of immersion in distilled water for 5 days and air drying at room temperature for 5 days. The samples were subjected to 5 cycles of alternating wetting and drying (Philbrick, 1950) unless the sample broke down to 90 per cent soil particles first, in which case a rating was assigned immediately.

Each sample was assigned a rating from 1 to 20 depending upon the degree of breakdown, in accordance with a subjective rating system devised by the author for the purposes of this study (Table VII). The upper and lower limits, i.e. 20 and 1, are considered to represent true "rock" and true

RATING SYSTEM FOR WET-DRY CYCLE TESTS

TABLE VII

Description of Residue		Numerical Rating
Slaking		
Breakdown to at least 90%* soil particles within :	4 days	1
	8 "	2
	16 "	3
	32 "	4
	64 "	5
Wet-dry cycles:		
Breakdown to at least 90% soil particles after	1 cycle	6
	2 "	7
	3 "	8
	4 "	9
	5 "	10
-Condition after 5 cycles		
50-90% soil particles		11
10-50% soil particles		12
66% - 1/16" - 1/8" lumps:		
remainder smaller		13
remainder larger		14
66% - 1/8" - 1/4" lumps:		
remainder smaller		15
remainder larger		16
66% - 1/4" - 1/2" lumps:		
remainder smaller		17
remainder larger		18
- badly cracked, or 2 to 3 lumps		19
- intact		20

*percentages based on volume

"soil", respectively, and those materials (soft rocks) with intermediate values are considered to form transitional materials (the grey zone). See Plate 15, Figure 1 for photographs of rocks with a range of wet-dry cycle ratings.

Results

The results of the slaking and wet-dry cycle tests are presented in Table III, column 25. The tests show that the Alberta rocks vary widely in degree of breakdown, with ratings ranging from 1 to 20. Ratings of samples from the Belly River Formation in the eastern part of the area range from 1 to 7, of the samples from the Edmonton Formation (including basal beds of overlying Paskapoo Formation) in the central part of the area from 1 to 14, and of the samples from the Saunders Group in the Western Plains and Foothills from 1 to 20.

Four of the 50 samples tested broke down almost immediately when immersed in distilled water (wet-dry rating = 1); 3 of these samples (SRW-39, MC-2, LA-9), which are representative of true "soils", were found in the Edmonton or Belly River Formations, with the remaining sample being a bentonite from Foothills (MRM-2). At the other limit of the scale (wet-dry rating = 20) are true "rocks" (shale) specimens from Cadomin in the Foothills region (Figure 1). Intermediary values generally increase from east-to-west across central Alberta and the significance of this increase is discussed in following sections.

Bond Strength

Bonds, as referred to here, include attractive forces or intermolecular bonds (e.g. van der Waals), intramolecular bonds (e.g. ionic bonds associated with recrystallization), cements (e.g. carbonates), *et cetera*. A quantitative strength evaluation of these bonds appears to be insurmountable. However, Terzaghi and Peck (1967) claim that a relative measure of the degree of bonding may be determined from the immersion of rock samples in water. The samples break down into fragments, the sizes of which are dependent upon the degree of bonding. The slaking test, i.e. submersion into water, was not sufficiently severe to evaluate the Alberta rocks hence, the wet-dry cycle test, which is more destructive, was employed following the slaking test.

To fully appreciate the merits of the test and its validity as a relative measure of bond strength, the mechanisms of the test must be examined.

The wet-dry cycle test imposes shrinkage and swelling forces within a sample. These forces are imposed internally and may or may not result in volume change depending upon the internal strength of the rock. If it is assumed that the bond strength of the rocks is less than the internal strength of the individual particles, then the forces of swelling and shrinkage are "testing" the inherent strength of the bonds. This assumption may be accepted, however, there are special cases which must be questioned, for example:

(1) A sedimentary rock with weak clastics (mica) and a strong cement (silica) would likely have failures within the individual particles.

(2) A rock in which abundant recrystallization has occurred may develop failures through the individual grains rather than at the points of recrystallization.

These are, as stated, special cases and may be considered unconsequential for the Alberta rocks.

The attraction and adsorption of water by fine-grained rocks leads to volume increase or swelling which promotes disintegration. The swelling of fine-grained rocks depends upon its clay mineral composition and salt content. Montmorillonite, for example has a great attraction for water along its basal planes. Since the rocks were immersed in distilled water, osmotic pressures also develop as the internal salt contents attempt to establish equilibrium. These forces tend to stress and break bonds in their attempts to bring about an increase in volume. The distribution of clay minerals and salts varies within even a small sample, therefore differential movements develop to promote breakdown. Also, dried samples take up water because of capillary action and the associated surface tension forces contribute to disintigration. The adsorption of water by any of the previously mentioned mechanisms occurs from the surface inward hence, air is entrapped and an explosive action may occur; along with rapid disintegration and a noticeable escape of air.

The forces associated with shrinkage generally arise from the pressure difference across the curved air-water interfaces of the voids. These forces establish differential movements and stresses within the sample which must be resisted by the interparticle bonds.

The force systems associated with shrinkage and swelling may be considered to act as "testing machines" to evaluate the strength of the internal bonds of a fine-grained rock. A limitation to the effectiveness of the slaking and/or wet-dry cycle test, however, arises because "the capacity of the testing machines" varies from sample to sample, i.e. the forces of swelling and shrinkage vary in accordance with such sample properties as clay mineral type and salt content which, in turn, vary from sample to sample. It must be realized, therefore, that the wet-dry rating evaluates the relative bond strength of rocks with respect to their resistance to the effects of air-drying and submersion in distilled water, i.e. a special testing environment. This factor does not, however destroy the value of the test or of the rating system because the strength of the bond with respect to distilled water (rain water in nature) and air-drying is of vital interest in the assessment of fine-grained rock competence.

The Alberta rocks exhibit a range of bond strengths from poorly bonded clayey siltstones (SRW-39, MC-2), silty claystones (LA-9), and bentonites (MRM-2) which are true "soils" (rating = 1) to very strongly bonded clayey siltstones (MRE-5,

MRR-9) (rating = 18 and 19) and true "rocks" (MP-series) (rating = 20). An increase in bond in bond strength of the rocks develops in an east-to-west direction across central Alberta in accordance with the increase in density and induration of the rocks (Figure 16). The influence of composition and density on bond strength are presented in Chapter VI with the results of a multivariate statistical evaluation. The influence of bond strength on the shear resistance characteristics of the Alberta rocks is discussed in Chapter VII.

Weathering

If the characteristics of the rock types are excluded, there are three main variables which influence the type and rate of weathering, namely, structure, climate, and topography. Structural features such as fissures, bedding planes, and faults determine the ease with which water may enter the rock. Climatic factors, e.g., temperature and humidity, influence the type of weathering process (chemical or physical) and the rate of weathering. Topography, in particular surface slope, controls the amount of rock exposure to weathering agents.

Weathering processes may be either physical or chemical. Significant physical processes which affect the Alberta rocks are expansion resulting from unloading and growth of crystals such as salt and ice. The chief chemical weathering process is hydration with oxidation, carbonation, and solution playing minor roles.

Both slaking and wet-dry cycle tests have been used to evaluate the susceptibility of fine-grained rock to weathering (Knight, 1963; Mead, 1936; Philbrick, 1950). Those Alberta rocks which are classed as bentonites disintegrated rapidly when submerged in distilled water (hydration); in outcrop these materials are always "mushy" on the surface. Further back in outcrop, the condition of the bentonite will depend on ground water conditions at the site; those strata which have little or no flowing water may be quite hard and a pick may be required to dislodge fragments.

Other Alberta rocks illustrate both in outcrop and laboratory test (slaking and wet-dry cycles), a definite increase in resistance to weathering in an east-to-west direction. The rocks of the Belly River Formation break down within two cycles of wet-dry testing. In outcrop these rocks are very soft and have a scale of "soil" at the surface; that is, they revert to a silt-clay complex.

Further west, in the Edmonton to Entwistle areas, the susceptibility to weathering decreases. The Edmonton area materials breakdown to at least 50% soil particles after five wet-dry cycles, while the Entwistle materials have two thirds of the original sample (by volume) in 1/16 inch to 1/8 inch fragments. The laboratory data once again parallels what is observed in outcrop. In the Edmonton area the bedrock in outcrop is soil-like or in soft fragments, whereas along the Pembina river near Entwistle the bedrock in outcrop is present

as relatively hard fragments which increase in size further into the slope. Talus slopes in this area are composed of rock fragments.

In the Edson-Foothills area, the resistance of the rocks to the wet-dry cycle test or to weathering increases. In the wet-dry cycle test the rocks either break down to fragments, some of which are up to one-half inch in dimension, or do not exhibit any deterioration at all. In outcrop the bedrock is indurated and fissured with fragments of a larger size than those to the east.

Compaction and Cemented Rocks

The wet-dry cycle test is often used (Philbrick, 1950) to distinguish between what Mead (1936) classified as compaction and cemented shales. Compaction shales are "soil-like" materials what have been consolidated by the weight of overlaying sediments and lack significant amounts of intergranular cement. Cemented shales are "rock-like" materials with significant amounts of cementing materials or strong bonds developed by recrystallization of the clay minerals. No sharp line of demarcation exists between these two rock types, nor is one possible, because most fine-grained rocks are partially cemented and partially compacted. The simple weathering test (wet-dry cycle test) appears to be the procedure which most clearly reveals the coherent quality of a fine-grained rock.

In discussing this test Philbrick (1950) states:

> "Those shales which are reduced by this process to uncohering aggregates of approximately grain-sized particles are compaction shales. Those which are entirely unaffected or reduce only to flakes are cemented shales. This test also indicates the behavior of the shale upon exposure to atmospheric conditions during construction."

Based on this statement all fine-grained rocks with a wet-dry cycle rating of eleven or less are considered as compaction rocks and those greater as cemented rocks. Thus, if an Alberta rock is classified as a compacted rock, at least 50 per cent of the sample breaks down to individual soil grains. On this basis the Alberta rocks are classed as compacted or cemented below:

East of Edmonton (Belly River Formation)	5 compacted	0 cemented
Edmonton Area (Edmonton Formation)	10 compacted	0 cemented
Entwistle Area (Paskapoo-Edmonton Formation)	4 compacted	6 cemented
Edson Area (Saunders Group)	2 compacted	11 cemented
Foothills Area (Saunders Group)	7 compacted	5 cemented

The above grouping shows that of the 50 rocks tested, 22 rocks are cemented and none of these are found in the eastern portion of the study area, whereas 28 rocks are compacted and 15 of these are found in the eastern portion and 13 in the western portion of the study area. Thus, all

of the samples of the Edmonton and Belly River formations are compacted, whereas in the Entwistle to Foothills area there are nearly twice as many cemented rocks as compacted rocks. The fine-grained rocks in the eastern half of the area revert to the nature of a highly fissured, overconsolidated clay upon exposure to the atmosphere, whereas the fine-grained rocks in the western portion generally appear as indurated rock fragments of a size dependent upon the strength of the bonds (as indicated by the wet-dry cycle rating).

Energy Considerations

The concepts of strain energy as proposed by Bjerrum (1967) are of interest because of the significant role he considered these concepts to play in the problems of slope stability in overconsolidated clays. Bjerrum treated strain energy concepts as a closed system, that is, he considered only the recoverable portion of the energy originally expended in the compression of the mass. A natural environment is not a closed system as Bjerrum suggests but is an open system because energy may be added, for example, by weathering processes. To illustrate, if a rock containing montmorillonite is subjected to weathering phenomena, the affinity of this mineral for water will bring about a volume increase. The magnitude of this increase will depend upon the weathering action and the system chemistry but not upon the energy imparted to the rock by compressive forces that acted during the early geologic history of the rock.

It is the inherent capacity of the fine-grained rocks of central Alberta to undergo volume change or to exhibit deformation upon reduction of overburden pressure and/or exposure to weathering phenomena that is of interest here. The major factors that influence the expansion of the Alberta rocks appear to be

(1) the energy supplied to the system during the compression of the deposits;

(2) the energy "dissipated" since deposition;

(3) the energy which may be recovered due to unloading;

(4) the strength of the bonds which may restrain energy release or volume change;

(5) the mineralogy and system chemistry of the deposit.

The amount of energy expended in compressing the Alberta rocks increases in an east-to-west direction because the past depth of burial of the present near-surface rocks was greater in the west than the east (Figure 1 and 4). As the Foothills are approached the amount of compression as derived from the compressive thrusts of the Laramide orogeny increases. No quantitative evaluation of the total amount of energy expended is available since neither precise measurements of erosion nor of tectonic forces are known.

The amount of energy "dissipated" or "lost" during the geologic history of the deposits is difficult to evaluate. Energy is "dissipated" by chemical alterations and recrystallization processes, both of which are associated with diagenesis.

Particle rearrangement during compression also uses up energy supplied.

In the compression of clay minerals, the energy employed to deform or bend the individual platelet is recoverable when the load is removed and the particle attempts to regain its original shape. An individual mica plate which was distorted by the transfer of overburden pressures through quartz grains is illustrated in a photomicrograph of a cemented siltstone (Plate 1, Figure 1). Presumably, if this rock were not cemented the mica plate would attempt to regain its original shape upon unloading, thereby producing strain. This same phenomenon likely occurs many times in a rock which contains a high percentage of extremely fine-grained micaceous matter or clay minerals, such as is illustrated in Plate 1, Figure 2. Hence, perhaps not only the clay minerals should be considered to provide strain, but all elastic particles with plate-like configurations, whether they be clay-, silt-, or sand-sized. Mineralogical studies reveal substantial amounts of clay minerals and micaceous matter in the fine-grained rocks of central Alberta, therefore, it is suggested that a considerable amount of energy is available during the unloading phase.

Interparticle bonds in a rock mass restrict expansion during rebound. The effectiveness of the restriction depends on the strength of the bonds, their susceptibility to weathering and the magnitude of the forces associated with rebound. As previously mentioned, the bond strength of the fine-grained

rocks of central Alberta show a definite increase in an east-to-west direction.

The clay mineral most susceptible to volume change is montmorillonite, because of its great affinity for water. It is commonly found in the Edmonton and Belly River Formation in the eastern part of central Alberta. Lesser amounts are found in the near-surface bedrocks of the Saunders Group in the western portion of the study area. Other clay minerals, illite, kaolinite, and chlorite, are relatively inert and do not have a great affinity for water, therefore contribute to only minor volume changes (other than contributions due to their plate-like form).

A true evaluation of the effects of salt contents is restricted because the cation type and concentration in the adsorbed state was not distinguished from that in the pore water. However, it is apparent that sodium salts are commonly associated with the presence of montmorillonite as illustrated by regression analysis (Table VIII). Since the adsorbed sodium ion is associated with high swelling conditions, greater volume changes are expected in the eastern portion of the study area.

The factors in favour and against the development of volume change or strain in the eastern and western portions of central Alberta may be summarized in general terms as follows:

TABLE VIII

CORRELATION COEFFICIENTS (r) FOR PETROGRAPHIC AND OTHER PROPERTIES OF FINE-GRAINED ROCKS FROM CENTRAL ALBERTA

	TEXTURES			COMPOSITION							PLASTICITY				BULK PROPERTIES					DISTANCE
	Clay	Q_{50}	Orien.	Mont.	Ill.	Na	Ca+Mg	P.W.S.	Org.	Carb.	w_L	w_P	I_P	A	γ_t	e	w_N	W.D.R.	C.E.C.	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	--	-.71	.28	.75	.50	.66	-.13	.01	.18	-.38	.73	.38	.78	.28	-.44	.34	.50	-.39	.30	.37
2	-.71	--	-.20	-.35	-.52	-.33	.31	-.35	-.24	.47	-.39	-.11	-.40	.00	.21	-.22	-.24	.07	-.09	-.30
3	.28	-.20	--	.15	.33	.11	.07	.15	-.08	-.27	.16	.24	.13	.00	-.19	.26	.10	-.09	.23	.03
4	.75	-.35	.15	--	-.22	.72	.15	.11	.06	-.21	.90	.64	.86	.53	-.77	.65	.72	.61	.63	.41
5	.50	-.52	.33	-.22	--	.10	-.24	-.05	.00	-.39	-.03	-.22	.02	-.32	.37	-.27	-.20	.26	-.26	-.24
6	.66	-.33	.11	.72	.10	--	-.20	.06	.01	-.18	.76	.26	.77	.50	-.30	.30	.28	-.52	.42	.14
7	-.13	.31	.07	.15	-.24	-.20	--	.72	-.34	.46	.02	.49	-.07	-.03	-.45	.16	.68	.06	.44	-.12
8	.01	-.35	.15	.11	-.05	.06	.72	--	-.30	.64	.14	.10	.13	.17	.05	-.18	.33	.31	-.06	-.11
9	.18	-.24	-.08	.06	.00	.01	-.34	-.30	--	-.45	.12	-.11	.15	.07	-.20	.23	-.05	-.26	-.15	.26
10	-.38	.47	-.27	-.21	-.39	-.18	.46	.64	-.45	--	-.26	-.58	-.22	-.07	.57	-.58	-.37	.68	-.44	.36
11	.78	-.39	.16	.90	-.03	.76	.02	.14	.12	-.26	--	.53	.99	.69	-.58	.50	.59	-.41	.43	.35
12	.38	-.11	.24	.64	-.22	.26	.49	.10	-.11	-.58	.53	--	.40	.17	-.68	.61	.79	-.40	.76	.17
13	.78	-.40	.13	.86	.02	.77	-.07	.13	.15	-.22	.99	.40	--	.72	-.52	.44	.48	-.37	.33	.35
14	.28	-.01	.00	.53	-.32	.50	-.03	.17	.07	-.07	.69	.17	.72	--	-.21	.15	.18	-.06	.14	.24
15	-.44	.21	-.19	-.77	.37	-.30	-.45	.05	-.21	.57	-.58	-.68	-.52	-.21	--	-.94	-.91	.75	-.72	-.51
16	.34	-.22	.26	.65	-.27	.30	.16	-.18	.23	-.58	.50	.67	.44	.15	-.94	--	.95	-.63	.60	.59
17	.50	-.24	.10	.72	-.20	.28	.68	.33	-.05	-.37	.59	.79	.48	.18	-.91	.95	--	-.72	.72	.36
18	-.39	.07	-.09	.61	.26	-.52	.06	.31	-.26	.68	-.41	-.40	-.37	-.06	.75	-.63	.72	--	-.53	-.53
19	.30	-.09	.23	.63	-.26	.42	.44	-.06	-.15	-.44	.43	.76	.33	.14	-.72	.60	.72	-.53	--	.05
20	.37	-.30	.03	.41	-.24	.14	-.12	-.11	.26	.36	.35	.17	.35	.24	-.51	.59	.36	-.53	.05	--

KEY - Col. 1: % clay content; Col. 2: median diameter, mm.; Col. 3: clay aggregate orientation; Col. 4: % montmorillonite content; Col. 5: % illite content; Col. 6: sodium ion content, milliequivalents; Col. 7: calcium plus magnesium ion content, milliequivalents; Col. 8: pure water salts content, milliequivalents; Col. 9: % organic matter; Col. 10: % carbonate content; Col. 11: liquid limit; Col. 12: plastic limit; Col. 13: plasticity index; Col. 14: activity; Col. 15: bulk density, p.c.f.; Col. 16: void ratio; Col. 17: % natural water content; Col. 18: wet-dry cycle rating; Col. 19: cation exchange capacity, milliequivalents; Col. 20: distance across strike, miles.

(1) western portion of central Alberta

(a) favour

- high energy from compression

(b) against

- low clay content
- low montmorillonite content
- low sodium content
- mainly cemented rocks

(2) eastern portion of central Alberta

(a) favour

- high clay content
- high montmorillonite content
- high sodium content
- all compacted rocks

(b) against

- low energy from compression

It is suggested here that the wet-dry cycle rating may provide an indication of the susceptibility of a fine-grained rock to undergo volume change upon reduction of over-burden load and/or exposure to weathering phenomena. A comparison of the effects of the above factors illustrates that greater volume change or strain occurs in the rocks in a west-to-east direction. This fact may be related to the wet-dry cycle ratings which decrease in magnitude in this same direction. That is, rocks which break down more readily

in the wet-dry cycle test (low values) are more susceptible to volume change or strain than those of high wet-dry cycle rating.

The cemented rocks from the western portion of central Alberta (mainly Saunders Group) appear to have relatively low propensity for progressive failure. In this region the diagenetic processes have progressed sufficiently so that that materials are essentially rock-like. On the other hand, the compacted rocks of the eastern portion of the study area (Edmonton and Belly River Formations) appear to be more susceptible to the mechanism of progressive failure as strain and volume change manifest themselves.

Between these two areas there is a transition zone of undetermined width where varying degrees of lithification have occurred. That is, in this transition zone, a particular bed may be more lithified than an adjacent bed due to such factors as mineralogy, etc. One would expect, therefore, to find problems of instability related to soils (e.g. slumping) and to rocks (e.g. falls and rock sliding).

Cation Exchange Capacity

The cation exchange capacity of the Alberta rocks was found by a titration procedure and the results are presented in Table III, column 24. The cation exchange capacity is not a significant parameter by itself but is used for the calculation of the pore water salt content. The cation

exchange capacity of the Alberta rocks varies substantially and reflects the percentage montmorillonite present as indicated by the regression analysis (Table VIII). The reason for this dependence is that the cation exchange capacity of montmorillonite is two to four times that of illite, kaolinite or chlorite, all of which are similar.

CHAPTER VI

STATISTICAL EVALUATION OF PETROGRAPHIC AND ENGINEERING PROPERTIES

Analysis of Results

The collection of large quantities of data from a variety of sources requires a rational system of evaluation to establish meaningful interpretations. Statistical analysis provides such a system, as it is concerned with the application of mathematical models based on probability theory to sets of observations (samples) from which predictions or generalizations can be extended to larger groups of phenomena (populations). Statistical techniques have been used in the earth sciences for more than a quarter of a century, and their application is now universal in all branches of geology. However, in soil mechanics conventional statistical procedures are seldom used, in spite of the fact that engineering geotechnical studies lend themselves to such treatment equally as well as studies in other fields. In this investigation several sets of samples were subjected to a variety of analytical techniques from which a large amount of data on the petrographic, chemical and derived

physical properties of the shallow bedrock materials of central Alberta were generated. In all, information on twenty properties, which lend themselves to a statistical evaluation, was collected from outcrop and corehole samples, although not all samples, for one reason or another, were subjected to the complete series of tests or analysis.

The first step in the analysis of this data was to calculate on the University of Alberta IBM 360 computor the linear regression equation[1] for each pair of variables, together with the corresponding sample correlation coefficient. Plots or scatter diagrams of the values for each variable pair also were obtained from the computor plotter in order to detect any noticeable departures from linearity.

Although the linear regression equations yield worthwhile information for certain variable pairs, a more useful statistic in determining the degree of association between variables is the correlation coefficient, r (Table VIII). This statistic has values ranging from -1 through 0 to +1, which indicates both the degree of association or correlation, i.e. (high or low, where 1 is perfect correlation) and the type of association (negative or positive). Its "significance" in terms of probability theory depends on the number of samples involved, but in practice the value of r which can be accepted as an indicator of a meaningful degree of association between the two sample attributes depends on the field of study (Snedecor, 1956). For this study, the

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[1] equations from Neville and Kennedy (1964)

value of the square of the correlation coefficient, r^2 has been used to define the levels of association, as indicated below.

r^*	r^2	degree of association
0.35	0.13	
		low
0.50	0.25	
		moderate
0.71	0.50	
		high
1.00	1.00	

* signs are disregarded

This rating is based on the fact that $r^2 \times 100$ is a measure of the percentage of variation in one variable associated with another. A cause and effect relationship is not implied, although it may exist. Thus, an r^2 value of 0.50 ($r = \pm 0.71$) means that 50 per cent of the variation in one variable is associated with the second (and visa versa), and the remainder of the variation is left unexplained (i.e. due to either sampling or technique error, or due to some other factor not accounted for in the analysis). Accordingly, the interpretation of the physical meaning of correlation between the two properties for which $r = \pm 0.50$ should be made with caution.

In most studies which involve a large number of variables, linear regression and simple correlation techniques are inadequate to assess the complex interrelationships among variables. Some alternative multivariate technique must be

sought, such as multiple regression analysis,[1] used here to evaluate interrelationships between properties arbitrarily designated "dependent" variables (y) and "independent" variables (x_1, x_2.........x_n). Such an analysis yields an equation of the form:

$$y = a + b_1x_1 + b_2x_2 + \ldots\ldots\ldots\ldots b_nx_n$$

The b values are the partial regression coefficients and indicate the average increase (or decrease) in the dependent variable per unit increase in the corresponding x, independent of the other variables in the equation.

Several procedures are available for evaluating the relative importance of the independent variables in the equation, i.e. for testing their relative statistical significance. These are discussed in a number of standard reference works on the subject, such as Snedecor (1956). However, no unique approach exists for the interpretation of multivariate systems in terms of causes and absolute effects; such an interpretation depends mainly on a knowledge of fundamental physical laws and their implied relationships to the system under investigation. This aspect of the analysis is brought out clearly in the succeeding sections of the report.

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[1] Multiple Linear and Nonlinear Regression Analysis for IBM 1620, IBM Library File No. 6.0.001, by Dan Leeson.

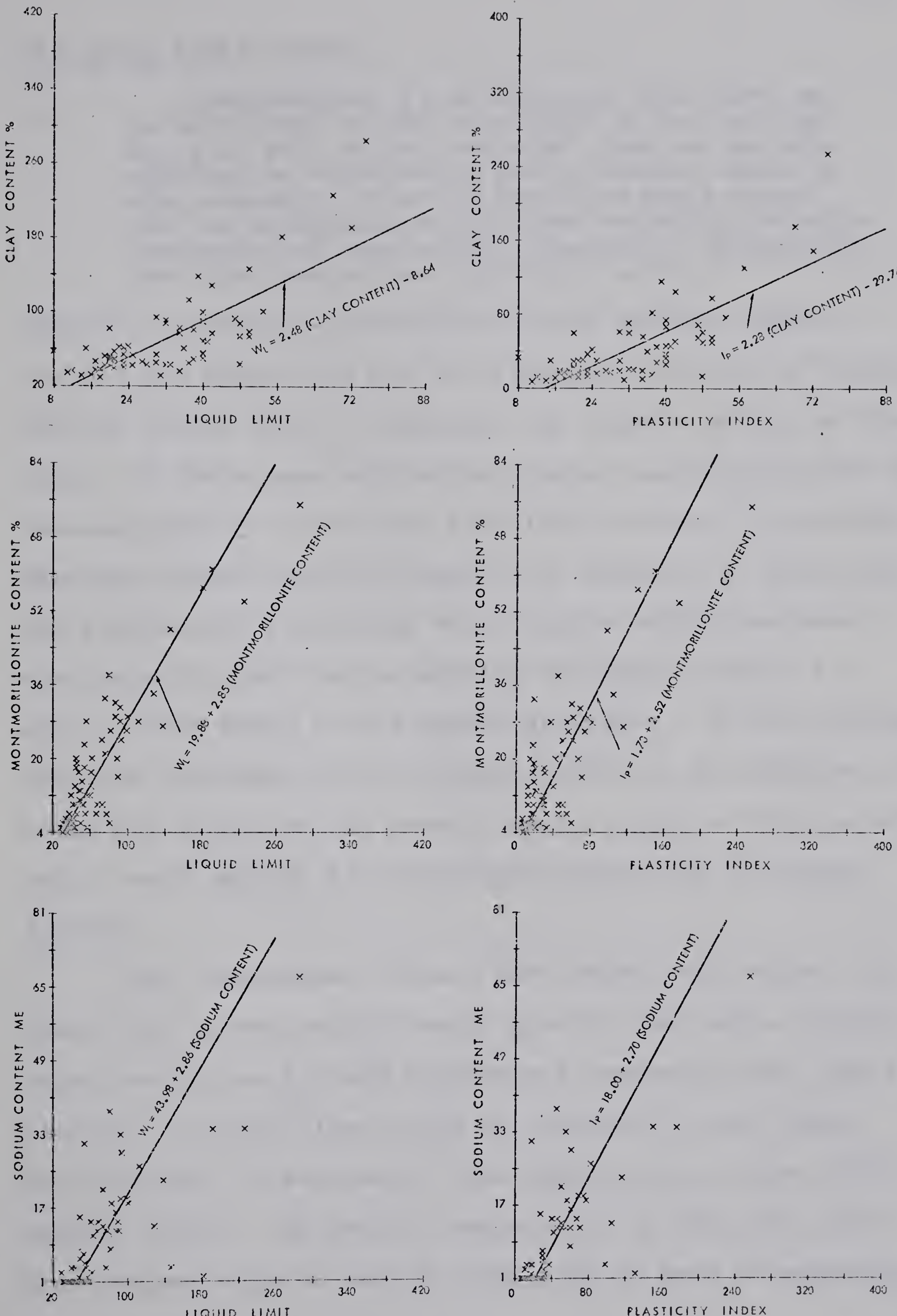
Plasticity

Interrelated variables associated with sample "plasticity" (liquid limit, plasticity index, activity) show moderate to high correlations with a number of other properties (Table VIII) notably montmorillonite content (in turn related to total clay content and sodium ion concentration) and, to a lesser extent, bulk density and related properties (void ratio, water content). Liquid limit and the closely associated ($r = 0.9877$) plasticity index show particularly high correlations with montmorillonite content and associated properties, whereas plastic limit and activity do not. This presumably is partially due to the lack of precision (operator and/or technique error) involved in the determination of plastic limits (Liu *et al*, 1965) although plastic limit values show slightly higher correlations with bulk density than do liquid limit values. It is also interesting to note that plastic limit values show a significantly higher correlation with cation exchange capacity than do the liquid limit values; obviously, the underlying causal relationships are somewhat dissimilar for the two properties.

Nothing new is advocated in the recognition of these relationships; the effects of clay composition and sodium ion content on plasticity have been reported by Grim (1962); Locker, (1963); Seed *et al*, (1964, a, b,) among others. Some of these relationships are illustrated in the scatter

diagrams in Figure 13 for the fine-grained rocks of central Alberta. It is of interest to note that for clayey soils, the clay portion of which by itself exhibits a liquid limit of approximately 300, Seed et al (1964 a, b,) report an increase in the liquid limit of the clayey soil of 25 with a corresponding increase in 10 per cent clay content. The Cretaceous-Tertiary fine-grained rocks exhibit a comparable increase if it is assumed that the clay content of all the rocks has a liquid limit in the order of 300 (e.g., sample W-6, Table III, which contains 75 per cent clay, has a liquid limit of 286). The rate of increase of the liquid limit of the Alberta rocks with increasing montmorillonite content is comparable to that reported by Seed et al (1964 a). However, Liu et al (1965) working with natural samples containing illite and montmorillonite found less pronounced increases in liquid limit with corresponding changes in either clay or montmorillonite contents. It is unfortunate that neither of these studies reported the influence of salt contents, which can alter the plasticity considerably and make any form of comparison difficult.

Among the other variables known to affect plasticity, organic matter has received attention (Casagrande, 1932; Liu et al, 1965).



RELATIONSHIPS OF CLAY, MONTMORILLONITE, AND SODIUM CONTENTS TO LIQUID LIMITS AND PLASTICITY INDICES

FIGURE 13

Liu _et al_ (1965) state:

> "Furthermore, it is believed that there may be variations in the "activity" of the various types of soil organic material that are as significant as those exhibited by various types of clay minerals. These differences may account for the divergence of opinions regarding relative importance of the organic fraction in controlling the index properties of natural soils."

However, no obvious correlation exists between organic content and plasticity for the fine-grained rocks of central Alberta (Table VIII). Possibly, the organic matter in these rocks, of Cretaceous and Tertiary ages, has been altered or "metamorphosed" to an inert coal-like material, in contrast to the more active material reported in deposits of Recent age. The increase in plasticity with organic matter has been attributed in part to the ability of organic matter to absorb water owing to its porous structure. If this is true, then the inertness of the organic matter in the Alberta soft rocks may be due to the denser, coaly nature of this material, which would inhibit its absorptive properties to varying degrees.

The correlation between pore water salt content and plasticity is not significantly greater than zero, despite experimental results and theoretical reasoning that show a decrease in liquid limit with an increase in pore water salt content, in particular with sodium (e.g., Grim, 1962; Locker, 1963). The lack of correlation in the soft rocks from central Alberta can be attributed in part to experimen-

tal or technique error in the determination of the pore water salt content as described previously. Similarly, calcium, magnesium, and potassium ion contents show no correlation with plasticity, however these cations are generally not sufficiently active to significantly influence the plasticity in regards to their salt contents in the pore water.

To evaluate the relative effects of clay composition and sodium content (cumulative value of adsorbed plus pore water contents) on plasticity, a multiple regression analysis was performed on the data given in Table III, with plasticity index the dependent variable (y) and the clay content, montmorillonite content, and sodium ion concentration the independent (and presumably "causal") variables (x's).

The solution to the analysis, which assumes linear relationships among the variables, yields a regression equation of the form:

plasticity index (I_p) = 0.6802 (clay content, %) + 1.4924 (montmorillonite content, %) + 0.9137 (sodium content, m.e.) -13.7960

The meaning is this: the plasticity index of the samples increases an average of 0.6802 for each per cent increase in clay sized material, 1.4924 for each per cent increase in montmorillonite, and 0.9137 for each milliequivalent increase in sodium ions. Thus, the equation not only provides an indication of the closeness of the association between changes in plasticity index and the independent variables but if the

relationships are statistically significant, they may be used to predict values for the dependent variable (plasticity index) from measured values of the independent variables.

The object of this study, however, is not to predict sample plasticity index values by regression analyses, as they can be measured quickly and efficiently by other means, but to establish the degree of association between plasticity index and related variables. In other words, the objective is to interpret the regression equation in terms of the relative contribution of each independent variable to variation in plasticity index values.

There is no unique approach to the interpretation of the results of multiple regression analysis because of the fact that the "independent" variables themselves are related (Snedecor, 1956; Krumbein and Graybill, 1965). Thus, the addition or subtraction of variables will change the entire complex to varying degrees, depending on the amount of intercorrelation among the variables. However, several standard approaches to interpretation are available. One is to calculate and compare the standard partial regression coefficients (b') described in Snedecor (1956, p.416 et seq.). The partial regression coefficients (b) themselves cannot be used directly to compare the relative contributions of each of the independent variables to the variation in the dependent variable, because in most cases the standard deviations of the independent variables are dissimilar.

The method employing the standard partial correlation coefficients was chosen because of its simplicity. None of the methods available lead to an unique answer because they are all susceptible to discrepancies, which are dependent upon the variables and the manner in which they are studied, because of the interdependence of the variables. In general, the method of analysis provides a search method for relevant variables on a substantive basis rather than on a predictive basis.

The employed procedure is demonstrated in conjunction with Table IX, the standard partial regression coefficients (b') for each of the independent variables (calculated from the partial regression coefficients in the multiple regression equation) are listed in the table. For ease of comparison, these values (b') have been recalculated as fractions of the highest standard partial regression coefficient (montmorillonite content), relative b' values. The value for R^2 (square of the coefficient of multiple correlation, R) represents the fraction of the total variation in the dependent variable (plasticity index) attributable to the regression.

In the first trial, in which all three independent variables are entered in the regression, montmorillonite content accounts for the largest portion of variation in plasticity index, with the two other independent variables being held constant. (The standard partial correlation coefficient, b' for one independent variable is representative

LINEAR AND MULTIPLE REGRESSION ON PLASTICITY INDEX

TABLE IX

Independent Variable	First Trial			Second Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	linear regression
clay content (%)	+ 0.6802	+0.3932	0.70	+ 0.8798	+0.5086	0.71	0.6015
montmorillonite content (%)	+ 1.4924	+0.5650	1.00	+ 1.8857	+0.7139	1.00	0.7452
sodium content (m.e.)	+ 0.9137	+0.2314	0.41	---	---	--	0.5933
a	-13.7960			-18.5972			
R^2	0.8129			0.7813			

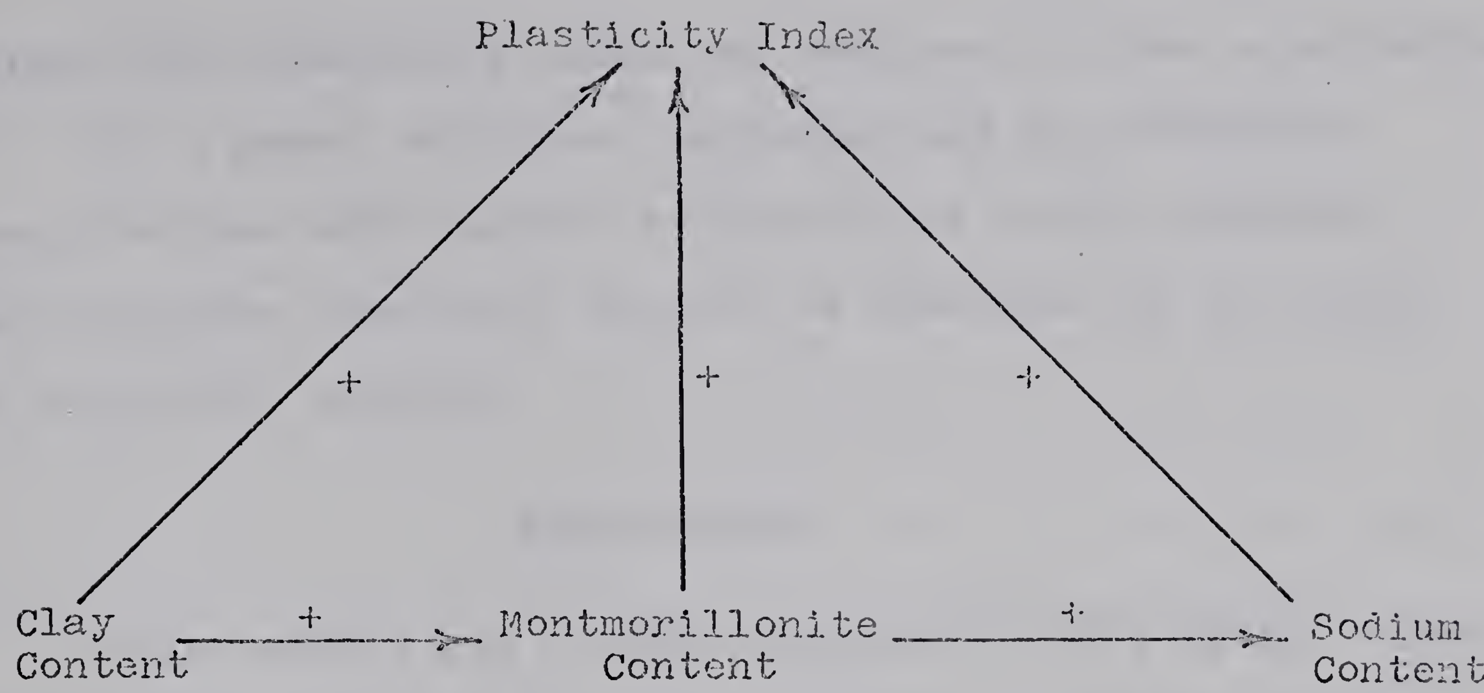
of the amount of variation in the dependent variable attributed to the considered independent variable when the other independent variables are held fixed). Clay content is next in its efficiency to predict plasticity index, and sodium ion concentration last. Together, the three variables account for or "explain" 81 per cent of the total variation in plasticity index values; the remaining 19 per cent is unaccounted for and is attributed to technique error or other hidden influential factors.

To evaluate further the relative importance of the three independent variables, the least efficient (sodium ion content) is omitted from the analysis, and the multiple regression equation recalculated for the two remaining independent variables. The corresponding standard partial regression coefficients are shown under the heading "second trial" in Table IX, from which it can be seen that montmorillonite is still the more important contributor to variation in the plasticity index. The R^2 value has dropped from 0.81 to 0.78, indicating only a minor loss (3 per cent) in the efficiency of the regression when sodium ion concentration is omitted. In other words, clay content and montmorillonite content together account for 78 per cent of the total variation in plasticity index values, with an additional 3 per cent associated with sodium ion concentration. If the linear regressions of the three independent variables on plasticity index are considered separately, the corresponding r^2

(square of the sample correlation coefficient) values show that montmorillonite content alone accounts for 74.5 per cent of the variation in plasticity index (Table IX). Since both clay content and montmorillonite content together account for 78 per cent of the variation, it can be inferred that the addition of clay content to the regression analysis explains only an additional 3.5 per cent of the variation in plasticity index.

The conclusion reached is that montmorillonite content is most efficient predictor of the variation in plasticity index of the soft rocks studied. The inclusion of closely correlated variables, clay content and sodium ion content, to the regression analysis increases the efficiency of the relationship only slightly. If the samples contained negligible amounts of montmorillonite, it could be assumed that total clay content would be the predominant factor controlling plasticity index. However, where montmorillonite content is variable, as it is in the samples under consideration, its influence on the plasticity index overshadows that of other related variables.

The interrelationships discussed above may be depicted in the form of a schematic "cause and effect" diagram, Figure 14 (after Miller and Kahn, 1962) in which some *a priori* knowledge of cause and effect exists.



SCHEMATIC DIAGRAM OF "CAUSAL FACTORS" RELATED TO PLASTICITY INDEX

FIGURE 14

In such a system the effects of one variable on another are indicated by an arrow; positive correlations are shown by a plus sign, negative ones by a minus sign. In the diagram, all of the variables show high positive correlations, from which it may be inferred that an increase in one is reflected by concomitant increases in the other three. Thus, if clay content is taken as the arbitrary starting point, an increase in this variable will cause an increase in montmorillonite content, which in turn will affect the sodium ion concentration. All three variables together show high positive corre-

lations with plasticity index, as confirmed by the experiments.

In a sense, all three variables may be considered causal factors with respect to plasticity index, although their relative importance varies, as indicated by the multiple regression analysis.

Bulk Density

Bulk density and related properties (void ratio, water content) show moderate to high correlations with a number of mineralogical, chemical, and physical properties of the fine-grained rocks from central Alberta (Table VIII). There also exists a moderate correlation between density and distance, the latter being defined as the distance across the strike of the strata from some arbitrary datum.

The important compositional variables are montmorillonite and carbonate content, although clay content also shows a distinct but slightly lower correlation with density. This latter point is to be expected as natural clay deposits generally have higher void ratios than granular deposits (Peck, Hanson, and Thornburn, 1953) because:

(1) granular mixtures are generally well graded with a tighter packing system than fine-grained deposits.

(2) granular systems are less active in a chemical sense and hence do not resist packing owing to factors such as large adsorbed water "hulls" or high repulsive forces found in clay sediments.

Thus, the Alberta rocks conform to theory by showing a decrease in bulk density with increasing clay content.

The same relationship holds true for bulk density and montmorillonite content. Developed from alteration of volcanic glass, montmorillonite naturally adsorbs considerable quantities of water, thus resulting in a less dense rock. Additional adsorption and swelling may take place upon erosion and rebound of montmorillonite-bearing sediments, resulting in a still lower rock density at or near the surface.

Carbonate content shows a moderate positive correlation with bulk density, to be expected if the carbonates are cements which are filling voids that would otherwise contain water. However, if the carbonates are clastics then they do not contribute to an increase in bulk density. The distribution of carbonates is erratic and the effect of carbonates on density is enhanced by a few samples that contain relatively high proportions of carbonate, whereas most contain little or none. If these few samples are excluded from the analysis then there is no apparent relationship between carbonate and bulk density.

Bulk density shows distinct negative correlations with plasticity index and Atterberg limits and also with the cation exchange capacity of the rocks. These relationships in turn can be attributed partly to the effect of montmorillonite, an increase in which tends to increase the values for Atterberg limits and cation exchange capacity but decrease the bulk

density of the samples. In other words, montmorillonite content is interpreted here as a causal factor, affecting both the chemical and derived properties or bulk properties of the rocks.

To evaluate more effectively the interrelationships between bulk density and other properties of the rocks, a multiple regression analysis was performed with bulk density the dependent variable (y) and per cent clay content, per cent montmorillonite content, per cent carbonate content and distance in miles across strike as independent variables (x's). The data are those given in Table III and includes both outcrop and subsurface samples. The analysis, which assumes linear relationships among the variables, yields the following equation:

bulk density, γ_t (p.c.f.) = 144.2806 + 0.2525 (clay content,%) -0.8274 (montmorillonite content,%) + 1.4081 (carbonate content,%) - 0.0396 (distance, miles).

As such the equation gives the impression that carbonate content is the most important variable associated with density, but examination of the data in Table X, in which the standard partial regression coefficients (b') and R^2 values, are tabulated, shows that this is not the case. The first trial which takes all four independent variables into account, suggests that montmorillonite content is the most effective predictor of density, followed by clay content

TABLE X

LINEAR AND MULTIPLE REGRESSION ON BULK DENSITY

Independent Variables	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	linear regression
clay content (%)	- 0.2525	+0.0567	0.48	+ 0.2555	+0.0573	0.47	+ 0.2369	+0.0531	0.40	0.1958
montmorillonite content (%)	- 0.8274	-0.1183	1.00	- 0.8545	-0.1222	1.00	- 0.9251	-0.1322	1.00	0.5869
carbonate content (%)	+ 1.4081	+0.0094	0.08	---	---	--	---	---	--	0.3207
distance (miles)	- 0.0396	-0.0339	0.29	- 0.0435	-0.0373	0.31	---	---	--	0.2572
a	+144.2608			+145.5565			+142.6293			
R^2	0.6966			0.6882			0.6578			

and distance. Carbonate content is quite ineffective in a relative sense, by a wide margin. Total variation in density explained by concomitant variation in the independent variables is 70 per cent.

The second and third trials which involve dropping the least effective variables in turn from the analysis and recalculating the pertinent statistics, show that montmorillonite content maintains its position as the most effective predictor with little loss of overall efficiency in the equation (from 70 to 66 per cent). However, clay content does contribute an additional 7 per cent to the "explainable" portion of the bulk density variation, if the R^2 value for the third trial (0.66) is compared with the r^2 value (0.59) obtained from the linear regression of montmorillonite content on bulk density alone. In other words, about two-thirds of the variation in density of the samples can be attributed to (or "explained by") variation in montmorillonite and clay content.

An equally interesting aspect of this analysis is found in the original multiple regression equation for density in which clay content is associated with a positive partial regression equation for density in which clay content is associated with a positive partial regression coefficient (+0.2525) and montmorillonite with a negative one (-0.8274). This situation persists through successive trials to the final equation in which only these two independent variables are kept:

bulk density γ_t (pcf) = 142.6293 + 0.2369 (clay content, %) -0.9251 (montmorillonite content, %)

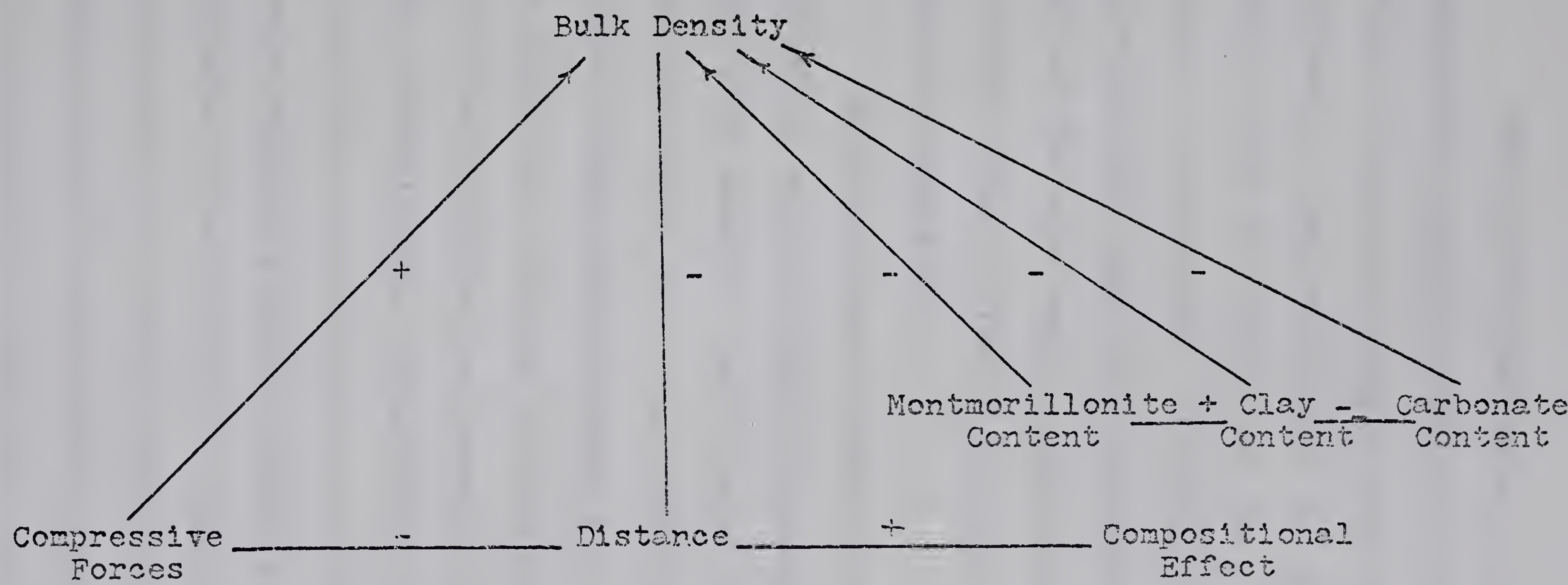
This means that the bulk density decreases with increasing montmorillonite content, in accordance with other experimental data. On the other hand, the bulk density increases with increasing clay content when montmorillonite content is held constant, which is the reverse of that obtained by looking at the regression of clay content on bulk density alone. No explanation can be provided for this confusing anomaly however, the significance of _a priori_ knowledge to interpretation of multiple regression analysis becomes readily apparent.

The question arises as to how to explain the 30 per cent of the variation in bulk density that cannot be attributed to the four independent variables discussed above. Part of this "unexplained" variation can be attributed to experimental error, as demonstrated graphically in Figure 12, where bulk density is plotted against distance across the strike of the rocks for both outcrop and corehole samples. The two regression lines, one for corehole samples and one for weathered outcrop samples, both show a progressive decrease in density away from Foothills (note previous discussion), however the main point is that a different, meaningful regression line does exist for each situation. Therefore, by grouping both the corehole and outcrop samples in the regression analysis without regard to their origin, some precision is lost and the "unexplained" portion of the variation in bulk density is affected. Also, experimental errors in

measuring clay and carbonate contents and especially montmorillonite contents augment the lack of precision in the regression analysis.

A portion of the "unexplained" variation in bulk density also can be attributed to potentially causal factors not included in the regression analysis. Cation concentration or pore water composition is one such factor which on theoretical grounds might affect the compressibility and hence the ultimate bulk density of the rocks. However, among the various chemical properties measured, only cation exchange capacity shows a moderate correlation with bulk density, in turn attributable to a common factor, montmorillite content. Moreover, it seems likely that some changes in cation content and composition have occurred since the deposition of the rocks. Thus, the chemical properties of the pore waters as now measured may differ radically from those properties which existed during compression of the rocks in Late Cretaceous and Tertiary times. Accordingly, it is difficult to interpret the present chemical properties of the samples in terms of cause and effect on bulk density.

The interrelationships between bulk density and associated attributes of the fine-grained rocks of central Alberta are summed up in the schematic diagram, Figure 15, in which "causal" factors are shown by arrows and noncausal factors by straight lines. Positive effects are indicated by plus signs and negative ones by minus signs.



SCHEMATIC DIAGRAM OF "CAUSAL" FACTORS RELATED TO BULK DENSITY

FIGURE 15

Two generalized causal factors are postulated; compressive forces (resulting from tectonic forces and overburden forces) and composition factors, both of which are related to (but not caused by) distance as measured eastwards across the strike of the strata (i.e. away from the source of sediments). Compressive forces, which presumably decrease away from the source of sediments (somewhere to the west of the area under consideration), cannot be measured directly; their effect is in part measured by distance, as shown in Figure 12.

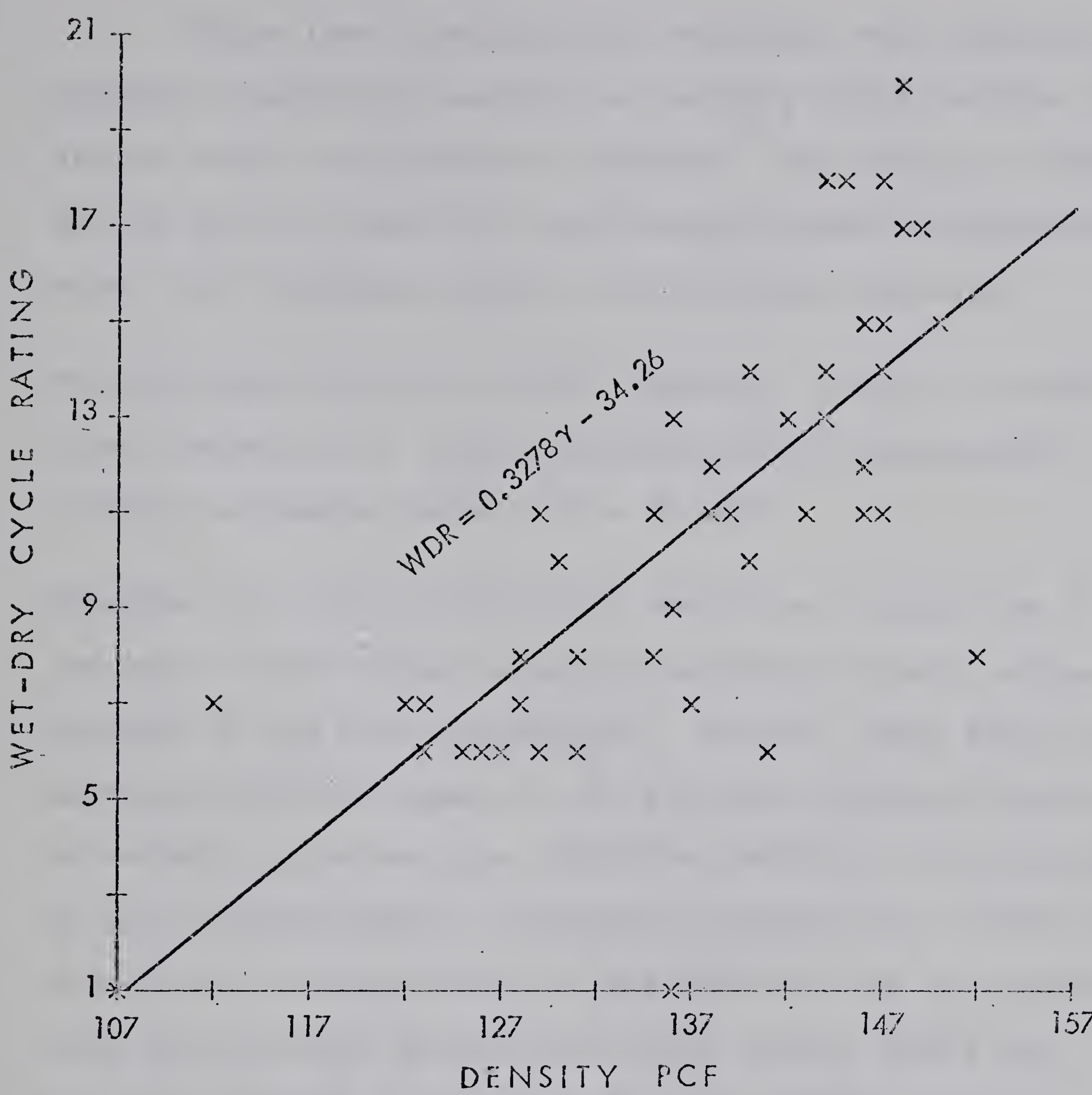
Distance also is associated with the compositional variables, each of which is measured as a percentage of the total rock sample. Each tends to increase in amount away from the source area (the direction in which the rocks as a whole become finer-grained i.e., more clayey), although the individual effects on bulk density are variable. Increases in montmorillonite content, the most important of the three compositional properties, decreases the bulk density of the rocks, providing the same effect as distance. However, because montmorillonite content and distance are positively correlated, the individual effects of the two variables on bulk density are "confounded" or scrambled. No unique procedure exists for unscrambling these effects and assessing each independent of the other, although regression analysis indicates that the montmorillonite content is the more important factor.

Similar interpretations can be made for the other independent variables, although the ultimate choice of "causal" relationships depends on a priori knowledge of fundamental physical laws.

Wet-dry Cycle Rating

Wet-dry cycle rating, obtained from the alternate slaking in water and drying test, is an attribute devised to evaluate among other factors, the inherent bond strength of the fine-grained rocks from central Alberta. Forces which "test" the strength of these bonds are developed internally in the sample, for example, swelling pressures, of which osmotic pressure is a major factor, and soil water tension during the drying phases of the test.

As measured on a ranking or ordinal scale, wet-dry cycle ratings of the Alberta rocks show moderate to high correlations with several compositional and physical properties of the samples (Table VIII). Among these are clay and especially montmorillonite content, both of which generate destructive shrinkage and swelling forces within the rocks (Yong and Warkentin, 1966). Carbonate cementation, on the other hand, enhances the cohesive forces, i.e. acts against the effects of wet-dry tests. Bulk density, as an indicator of overburden (vertical) and tectonic (horizontal) pressures can be related to particle packing and thus should inhibit the effects of wet-dry tests (Figure 16).



WET-DRY CYCLE RATING vs. DENSITY FOR THE

ALBERTA ROCKS

FIGURE 16

These four "independent" variables were selected for multiple regression analysis of wet-dry cycle ratings, the latter being the dependent variable. The analysis, based on the data in Table III and assuming linear relationships among the variables, yields the following equation:

Wet-dry cycle rating = 0.2923 (density, p.c.f.) + 0.0058 (clay content,%) + 0.0285 (montmorillonite content,%) + 0.6807 (carbonate content,%) - 30.6779

Together, the four independent variables account for 71 per cent of the total variation in wet-dry cycle ratings, leaving 29 per cent unexplained. However, bulk density and carbonate content appear to be the most efficient predictors of wet-dry cycle ratings, which is confirmed by calculation of the standard partial regression coefficients (Table XI). Successive recalculations of the equation and the corresponding coefficients (second and third trials, Table XI), in which the lowest variable is dropped, confirm this interpretation; neither clay content nor montmorillonite content account for any additional variation in wet-dry cycle ratings not associated with the other two independent variables. If bulk density is considered alone ($r^2 = 0.56$), then only 56 per cent of the variation in wet-dry cycle ratings is accounted for, the remaining 15 per cent being attributable to carbonate content.

LINEAR AND MULTIPLE REGRESSION ON WET-DRY CYCLE RATING

TABLE XI

Independent Variable	First Trial			Second Trial			Third Trial			r^2 linear regression
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	
density (p.c.f.)	+ 0.2923	+3.4433	1.00	+ 0.2948	+3.4727	1.00	+ 0.2689	+3.1676	1.00	0.5635
clay content (%)	+ 0.0058	+0.0146	0.00	---	---	--	---	---	--	0.1493
montmorillonite content (%)	+ 0.0285	+0.0403	0.01	+ 0.0347	+0.0490	0.01	---	---	--	0.3767
carbonate content (%)	+ 1.9307	+0.1633	0.05	+ 1.9252	+0.1629	0.05	+ 1.9093	+0.1615	0.05	0.4634
a	-30.6779			-30.9489			-26.9455			
R^2	0.7091			0.7090			0.7067			

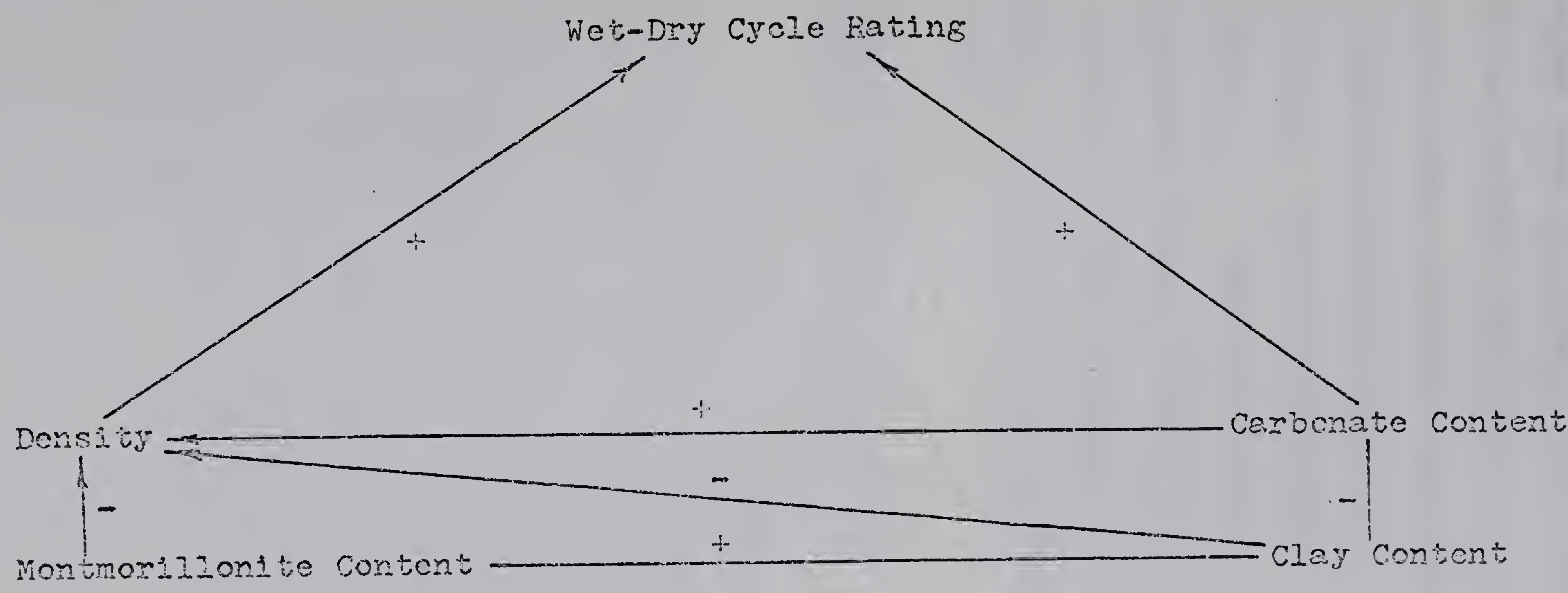
These findings are in line with the theoretical expectations, bulk density being a measure of the inherent bonding of the rocks, and carbonate content a measure of chemical cementation. It might be expected that montmorillonite would play a major important role, but again, the interrelationships between the dependent and independent variables are masked to some extent by moderate to high correlations among the latter. Schematically, these relationships are summed up in Figure 17, in which arrows indicate causal effects and straight lines non-causal associations.

Miscellaneous Correlations

In addition to the relationships among the various properties of the Cretaceous-Tertiary soft rocks of central Alberta established by means of multiple regression analysis in the proceeding sections, a number of additional variable-pair relationships remain to be discussed (Table VIII). In some of these cases, it is the lack of a significant correlation between properties that is of interest.

Particle Orientation

Particle orientation does not exhibit well developed relationships with the other properties. The highest correlation ($r = 0.3297$) is with illite content, undoubtably reflecting the fact that this constituent shows up in thin sections cut perpendicular to the bedding as minute shreds or plates



SCHEMATIC DIAGRAM OF "CAUSAL" FACTORS
RELATED TO WET-DRY CYCLE RATING

FIGURE 17

which tend to enhance the visual particle orientation effect. It is possible that part of the lack of correlation between orientation and other variables is due to the difficulty in quantitatively measuring this property certainly, the procedure used in this study is subjective and lacking in precision. The fact remains, however, that a distinct impression has been obtained from examination of numerous thin sections of rocks from across central Alberta that the presence of well-developed particle orientation is a "random" effect.

Median Diameter, (Q_{50}, m.m.)

As expected, the sample median diameter, a measure of grain size, exhibits a correlation trend similar to that of clay content. Both variables are determined from the same grain-size frequency surve, and as a result, show a moderately high negative correlation. However, it is worth noting that the absolute values of the two sets of correlation coefficients are generally lower for the median diameter; this suggests that clay content is the more useful (or efficient) parameter for evaluating relationships between texture and other rock properties.

Chemical Composition

The pore water salt content is related to carbonate content and hence also to calcium and magnesium ion concentration. However, it does not exhibit a significant correlation with plasticity or bulk properties as previously stated. The sodium ion concentration, on the other hand, shows relationships with other properties in much the same manner as montmorillonite content but the correlation coefficients (r) are seldom as high.

Mineral Composition

The most outstanding correlations in the entire statistical analysis are those associated with montmorillonite; this mineral exhibits high correlations with all plastic and physical properties. Illite, a commonly occurring clay mineral in soft rocks of central Alberta exhibits low to negligible correlation with plasticity and bulk properties, in a way reflecting its relatively inactive nature. As stated above, the carbonate content of the soft rocks has some influence on the concentration of the salts in the pore water; this relationship is to be expected for the soft rocks studied because they generally only have high salt contents when carbonates are present. The carbonate content does (as discussed previously) influence the wet-dry cycle rating and its related factors. The organic content of the rocks appears to have a "random" effect, similar to particle orientation, on the materials studied.

CHAPTER VII

SHEAR STRENGTH

Recent studies of slope stability in overconsolidated clays and clay-shales have emphasized the application of peak and residual shear strength concepts. (Skempton, 1964; Bjerrum, 1967). The fine-grained rocks of central Alberta appear to increase in shear resistance in an east-to-west direction as exemplified by a decrease in propensity for slope failure in that direction. Thus, it is desirable to determine peak and residual strength parameters and relate these parameters to other geotechnical characteristics of the Alberta rocks.

Description of Rocks Studied

Drained direct shear tests were performed on two soil types from each of the coreholes drilled for this study (coreholes 1, 2 and 3, Figure 1) To augment the data obtained from these tests, drained direct shear results for the Edmonton area were selected from the River Bank Stability Report (Department of Civil Engineering, 1969) and from the Lesueur slide area (Pennell, 1969).

The pertinent properties of the fine-grained rocks are summarized in Tables XII and XIII (additional information on

TABLE XII

SUMMARY OF SHEAR STRENGTH DATA AND RELATED PROPERTIES OF FINE-GRAINED ROCKS OF CENTRAL ALBERTA

SAMPLE		SHEAR STRENGTH							TEXTURE			COMPOSITION				PLASTICITY		BULK PROPERTIES			
Number	Depth	σ	τ_p	τ_R	ϕ_p	C_p'	ϕ_R'	C_R'	Sand	Silt	Clay	Mont.	Chl.+ Ill.	Carb.	Org.	w_L	I_P	γ_t	e	w_N	W.D.R.
	ft.	psi	psi	psi	degs.	psi	degs.	psi	%	%	%	%	%	%	%			pcf		%	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
SRW-39A	39.8	72.1	74.2	TI	23.0	43.3	6.5	17.1	10	54	36	14	18	ND	1.4	60.6	37.5	135.7	.42	15.5	4
-39B	39.9	117.9	92.8	30.1												NP		NP		13.6	
-39B	39.9	145.4	NP	33.4												NP		NP		13.6	
-39C	40.0	35.5	58.0	20.5												NP		NP		11.6	
-39C	40.0	72.1	NP	26.3												NP		NP		11.6	
SRW-39R[1]	40.4	53.8	NP	20.5	NP	NP	20.0	0.2	Same as SRW-39A							59.8	31.2	125.5	.57	20.8	NP
	to	99.6	NP	35.0																	
	41.3	145.4	NP	53.8																	
SRW-53A	52.5	53.8	57.8	TI	36.5	20.4	18.5	3.0	26	49	23	26	14	ND	1.6	69.1	40.7	132.5	.37	13.9	NP
-53B	52.3	99.6	94.8	36.2												69.1	40.7	132.8	.38	14.1	
-53C	51.8	145.4	127.4	52.0												73.5	42.1	132.2	.31	11.7	
-53D	51.5	53.8	NP	21.2												87.4	59.2	130.5	.40	15.1	
SRW-53CP[2]	53.0	53.8	NP	17.5	NP	NP	14.9	0.4	Same as SRW-53A							70.2	42.5	131.2	.36	12.3	
		99.6	NP	24.5																	
		145.4	NP	38.7																	
LA-9A	94.5	-	-	-	22.5	1.0	10.0	5.2	5	27	68	54	14	ND	0.5	226.5	175.4	112.4	1.02	36.3	7
LA-9CP[2]	-	-	-	-	NP	NP	8.5	1.4	Same as LA-9A												
RB-1A	113.0	From: U. of A.			25.0	0.0	8.5	4.5	17	38	45	43	2	ND	0.4	147.0	93.0	112.0	-	40.0	NP
RB-2A	0.5	River Bank			14.0	6.0	8.0	4.5	3	5	92	92	0	ND	0.5	182.0	131.0	103.0	1.64	60.0	NP
RB-3A	110.0	Stability Rept.			28.0	6.9	12.0	2.5	29	41	30	22	3	ND	1.0	62.0	61.0	115.0	.67	29.0	NP
P-54A	54.7	53.8	109.2	33.1	32.5	59.0	13.0	17.5	0	70	30	10	17	1.54	0.5	40.0	16.1	143.1	.30	10.9	11
-54B	54.3	99.6	137.3	45.0												41.2	18.3	143.6	.31	11.8	
-54C	54.4	145.4	129.0	46.0												49.6	25.2	144.6	.30	12.5	
-54D	54.5	145.4	195.2	56.4												50.3	26.7	141.0	.36	13.9	
-54E	54.2	122.5	99.6	NP												50.0	28.8	143.7	.32	12.3	
-54G	54.0	76.7	84.8	28.0												51.3	27.6	144.9	.31	11.3	
-54R[1]	55.0	53.8	NP	28.6	NP	NP	26.8	0.7	Same as P-54A							38.7	18.3	129.9	.40	14.5	NP
		99.6	NP	49.5																	
		145.4	NP	74.3																	
P-69A	70.5	53.8	149.1	27.1	43.0	105.0	20.5	6.1	18	75	7	8	9	ND	0.3	45.9	15.7	139.9	.35	12.6	14
-69B	70.3	99.6	210.5	41.6												42.9	8.8	142.2	.32	11.5	
-69C	70.1	145.4	243.6	61.4												42.8	8.8	142.2	.32	11.5	
-69D	69.9	145.4	231.0	TI												42.0	10.5	141.3	.31	12.0	
-69F	69.7	99.6	196.9	TI												46.4	15.3	141.8	.33	12.0	
MSR-45A	45.0	53.8	107.4	34.3	29.7	95.6	22.5	9.5	38	43	19	5	12	ND	0.3	31.2	10.9	143.5	.25	8.8	13
-45B	45.2	99.6	162.9	50.5												29.0	7.5	147.3	.22	10.1	
-45C	45.3	145.4	183.0	66.1												30.8	10.1	145.7	.28	9.4	
-45D	45.5	145.4	167.1	69.8												24.0	6.3	145.3	.32	11.3	
-45E	41.5	99.6	178.8	45.9												33.0	7.7	147.8	.26	9.7	
-45F	44.9	53.8	144.5	39.0												33.2	9.4	145.3	.36	8.9	
-45G	44.7	53.8	124.8	27.0												30.2	5.4	147.2	.26	8.7	
-45H	43.5	99.6	164.8	NP												38.1	15.3	147.0	.23	9.9	
-45I	45.7	145.4	163.3	73.8												29.2	7.3	143.0	.26	8.7	
-45J	45.9	53.8	109.5	27.6												29.2	7.3	148.0	.26	8.7	
MRR-74A	74.8	53.6	151.8	40.3	34.2	109.3	32.0	5.6	10	82	8	5	3	2.4	0.1	46.6	23.6	145.1	.25	8.4	17
-74B	75.2	99.6	226.1	67.3												46.6	23.6	147.0	.27	9.5	
-74C	75.3	145.4	313.6	95.1												43.5	20.2	147.9	.27	9.5	
-74D	75.4	145.4	305.2	NP												43.5	20.2	149.6	.23	8.0	
-74E	75.6	99.6	270.7	72.2														147.3	.23	8.0	
-74F	75.1	53.8	183.3	36.5														147.6	.27	9.7	
-74G	75.0	104.8	239.0	70.2														147.0	.27	9.7	
MRR-74CP[2]	75.9	53.8	NP	24.3	NP	NP	23.9	0.4	Same as MRR-74A							41.1	19.0	149.6	.24	8.4	NP
		99.6	NP	44.4																	
		145.4	NP	64.3																	
MRR-74R[1]	74.5	53.8	NP	31.2	NP	NP	25.5	5.0	Same as MRR-74A							35.7	14.6	125.5	.49	17.5	NP
		99.6	NP	51.3																	
		145.1	NP	74.9																	

[1]R = remoulded samples; [2]CP = cut plane samples.

KEY - Col. 3 (Normal stress, pounds per sq. inch), Col. 4 (Peak shear strength, pounds per sq. inch), Col. 5 (Residual shear strength, pounds per sq. inch), Col. 6 (Peak angle, degrees). Col. 7 (Peak cohesion, pounds per sq. inch). Col. 8 (Residual angle, degrees), Col. 9 (Residual cohesion, pounds per sq. inch); NP = not performed, TI = test incomplete. Col. 13 (Montmorillonite), Col. 14 (Chlorite plus illite), Col. 15 (Carbonate), Col. 16 (Organic matter) ND = not detected. Col. 17 (Liquid limit), Col. 18 (Plasticity index) NP = not performed, Col. 19 (Bulk density, pounds per cubic foot), Col. 20 (Void ratio), Col. 21 (Natural water content), Col. 22 (Wetting-drying rating). NP = not performed.

TABLE XIII

PETROGRAPHIC PROPERTIES OF DIRECT SHEAR SPECIMENS AS DETERMINED FROM THIN SECTIONS

SAMPLE NUMBER	DISTANCE (miles)	< 20 MICRONS (%)[2]	MONTMORILLONITE (%)[3]	COLOR	STRUCTURE				TEXTURE			COMPOSITION						
						Laminations												
					Homo.	Org.	Clay-silt	Pell.	% >20 μ	Silt size	% clay orient.	Q.+F.	R.F.	Micas	Mont.	Org.	Pyr.	Carb.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SRW-39A	197	30	14	Gr		X	X		25	C	10	Ab	P	P	P	Ab		P
B				Gr-Br		X	X		10	C	10	Ab	P	P		Ab	P	
R[1]				Br-Gr	X				30	C	10	Ab	P	P		Ab		P
SRW-53A	197	48	26	Br-Gr			X		20	C	0	Ab	P	P			P	P
B				Br-Gr			X		20	C	0	Ab	P	P	P	P	P	
C				Gr			X		30	C	10	Ab	P	P			P	P
D				Br-Gr			X		25	C	0	Ab					P	
P-54 A	112	10	10	Gr		X	X		10	M	10	Ab		P		Ab	P	P
D				Br		X			0		30					Ab		
G				Br		X			.0		10					Ab		Ab
R[1]				Gr-Br				X	10	M	0	Ab		P		P	P	P
P-69 A	112	35	8	Gr		X			5	M	10-20	P		P			P	
B				Br		X			10	M	20-30	P		P	P	P	P	
MRR-45A	59	65	5	Br-Gr	X				40	C	10	Ab	P	P			P	P
B				Gr	X				40	C	10	Ab	P	P				P
C				Gr	X				35	C	10	Ab	P	P				P
D				Gr	X				30	C	10	Ab	P	P			P	P
E				Gr	X				35	C	10	Ab	P	P				P
F				Gr	X				55	C	10	Ab	P	P			P	P
G				Gr	X				45	C	10	Ab	P	P			P	P
I				Gr	X				40	C	10	Ab	P	P			P	
J				Gr	X				45	C	10	Ab	P	P				
MRR-74B	59	62	5	Gr	X				70	C	0	Ab	P	P				Ab
C				Gr			X		50	C	0	Ab	P	P				Ab
D				Gr			X		35	C	0	Ab	P	P				Ab
E				Gr			X		75	C	10	Ab	P	P				Ab
F				Gr		X	X		25	C	10	Ab	P	P				Ab
G				Gr			X		40	C	10	Ab	P	P				Ab
R[1]				Gr			X		1	M	10	Ab	P	P				Ab

[1] R = remoulded samples. [2] From hydrometer analysis. [3] From grain size and X-ray data.

KEY - Col. 5: Br = brown, Gr = grey, Cols. 6-9 (Homogeneous, organic, clay-silt, pelleted): X = present; Col. 11: M = medium, C = coarse; Cols. 13-19 (Quartz plus feldspars, rock fragments, micas, montmorillonite, organic matter, pyrite, carbonates): P = present, Ab = abundant.

each sample series is presented in Table III). A brief generalized description of each sample series follows:

Marlboro Corehole

MRR-45	:	a grey, carbonate cemented siltstone of medium plasticity; no organic matter; high quartz and feldspar content; illite as major clay mineral.
MRR-74	:	a grey, carbonate cemented siltstone of high plasticity; no organic matter, very high quartz and feldspar content; very low clay content; laminated structure.

Entwistle Corehole

P-54	:	a dark grey, compacted siltstone of medium plasticity; abundant organic matter; very fine-grained micaceous material; montmorillonite and illite present; moderate carbonate content.
P-69	:	grey-green, cemented, sandy siltstone of medium plasticity; low organic content; quartz, feldspar, mica, montmorillonite, and illite present.

Edmonton Corehole

RB-1A	:	greenish-grey, compacted, bentonitic clay stone of very high plasticity.
RB-2A	:	greenish-yellow, almost pure, bentonite of very high plasticity.
RB-3A	:	brownish-grey, compacted, sandy clayey siltstone of high plasticity.
LA-9A	:	greenish-grey, compacted, bentonitic silty claystone of very high plasticity.

Waskatenau Corehole

SRW	:	brownish-grey, compacted, clayey siltstone of high plasticity; abundant organic matter; quartz and feldspar; montmorillonite as the major clay mineral.

Waskatenau Corehole (cont'd)

SRW-53 : grey, compacted, sandy clayey siltstone of high plasticity; little organic matter; abundant quartz and feldspar, montmorillonite as major clay mineral.

Direct Shear Tests

Sample Preparation

The relatively undisturbed corehole samples from the Edmonton Formation (Waskatenau) were cut to fit the direct shear box (6 cm. x 6 cm. x 2.54 cm.) with a band-saw and a sharp blade however, samples from the Saunders Group (Marlboro and Entwistle) were too indurated to suit this procedure. These samples were cut to approximate size by a diamond saw and then ground to true size with silicon carbide grit on a lap wheel. Water was employed as a cutting lubricant since the cutting time was so short and the permeability of the samples so low that significant changes in water content could not occur. The samples were wiped dry after the cutting operation. Both cutting procedures require care and caution to acquire a sample of true size because blade vibrations tend to promote fissuring and chipping. Samples with precut failure planes were cut on the diamond saw to ensure a true precut surface.

Remoulded samples were consolidated in a large oedeometer from a water content slightly higher than the liquid limit to a final pressure of 25 tons per square foot. These samples were trimmed to size with a sharp blade.

Description of Apparatus

To facilitate determination of residual strength parameters, the standard Clockhouse direct shear machine was modified to allow automatic reversal of the shear box, by utilizing a time clock to reverse the power supply to the motor at precalculated (displacement) time intervals.

Loads and displacements were measured with calibrated 2000 pound load cells and linear variable differential transducers (LVDT), respectively. Readings of these instruments were taken automatically and printed out with the aid of a digital recorder (Rennie, 1968 for details).

Test Procedure

Each test specimen of sample series was placed into the shear box and subjected to a normal load of 53.8, 99.6 or 145.4 psi (Series SRW-39 was the first series tested and different normal loads were employed for no specific reason.) All specimens were submerged in distilled water in the shear box and the normal load was applied in one increment. Vertical deformations noted under the normal loads were generally either very small or non-existant. The vertical movements were attributed to consolidation and seating of the specimen into the ribbed drainage plates hence, plots of deformation versus time were not typical time curves. However, with those rocks which exhibited vertical deformation, the influence of the normal load was considered complete after

the "time curve" hooked and approached a gentle slope. With many of the rocks, in particular those from the western portion of the study area, no appreciable deformation was noted.

When the vertical deformation was considered complete, the shear force was applied at a predetermined rate of displacement. The samples were subjected to a shear displacement of 0.1 inches, during which the peak resistance was always exceeded. The samples were then displaced in a reverse direction, past their original positions, and on for another 0.1 inches; this procedure was repeated with total displacements of 0.2 inches per reversal cycle until the shearing resistance had dropped to a steady minimum value (residual strength). The displacement of 0.1 inches in either direction was chosen because; (a) the construction of the direct shear box promoted loss of soil at greater displacements, (b) no correction for change of area, as caused by shearing displacement was made, therefore it was desireable to keep the effects of such at a minimum.

The number of direct shear tests performed per Mohr envelope varied from one sample series to another. The testing of a sample series was not considered complete until either a well defined envelope was achieved or all available samples were used.

After the direct shear tests were complete, the samples were bound together with rubber tape and impregnated with

Carbowax 6000 to keep the sample intact for thin sectioning. The carbowax did not cause further disintegration of these samples, as it did with the outcrop samples, perhaps because they were fully saturated. In this case epoxy cement was used to cement the specimens to the glass plates. The thin sections formed a plane parallel to the direction of shear and parallel to the normal stress (perpendicular to the bedding) thereby incorporating the failure plane.

Rate of Displacement

The rate of displacement for the determination of effective strength parameters must be slow enough to ensure fully drained conditions. A suitable rate can be established by a trial and error procedure or by a theoretical equation (Bishop and Henkel, 1957). The trial and error procedure was not suitable for this study because: (a) the strength of the soft rocks studied is so variable that an evaluation of different trial rates of strain would be open to question, (b) insufficient samples and time were available for a detailed study of each rock type. The theoretical equation utilizes the theory of consolidation and available equipment was of insufficient capacity to determine the consolidation characteristics of the majority of the rocks studied. Thus, the rate of displacement chosen for the determination of peak strength, i.e. 7×10^{-5} inches/minute, was based on previous investigations in the Edmonton Formation rocks

(Sinclair and Brooker, 1967) and on the findings of Van Auken (1963) on similar materials. This rate of deformation allows the strength results to be compared on a common basis. A detailed investigation of the rates of deformation was not warranted as it was not considered to be a factor under study. In addition, the very magnitude of a program dealing with the rates of deformation precluded its inclusion in this project.

If the rate of deformation is kept within the normal range used in direct shear tests, it has little influence on the residual strength parameters (Sinclair and Brooker, 1967; Kenney, 1967). The rate of displacement, 1.54×10^{-3} inches per minute, was chosen to facilitate the use of the time clock for automatic reversal and the use of the digital recorder (i.e., the time clock was mechanically limited to a minimum time increment and test time of 2 hours allowed the recorder to acquire sufficient readings). A rate of displacement of 5.0×10^{-3} inches (4 hours per cycle) provided identical results to the chosen rate, however a rate of 1.53×10^{-2} inches (13 minutes per cycle) caused an increase in shear resistance of approximately 10% (Figure 18 illustrates a typical case.) Similar results are reported by Pennell (1969) in his studies on fine-grained rocks from central and northern Alberta, however de Beer (1967) reported the opposite trend with the Boom clay, i.e. tests at higher rates of deformation gave lower residual shear angles then the more slowly performed tests. No explanation can be offered for this anomoly

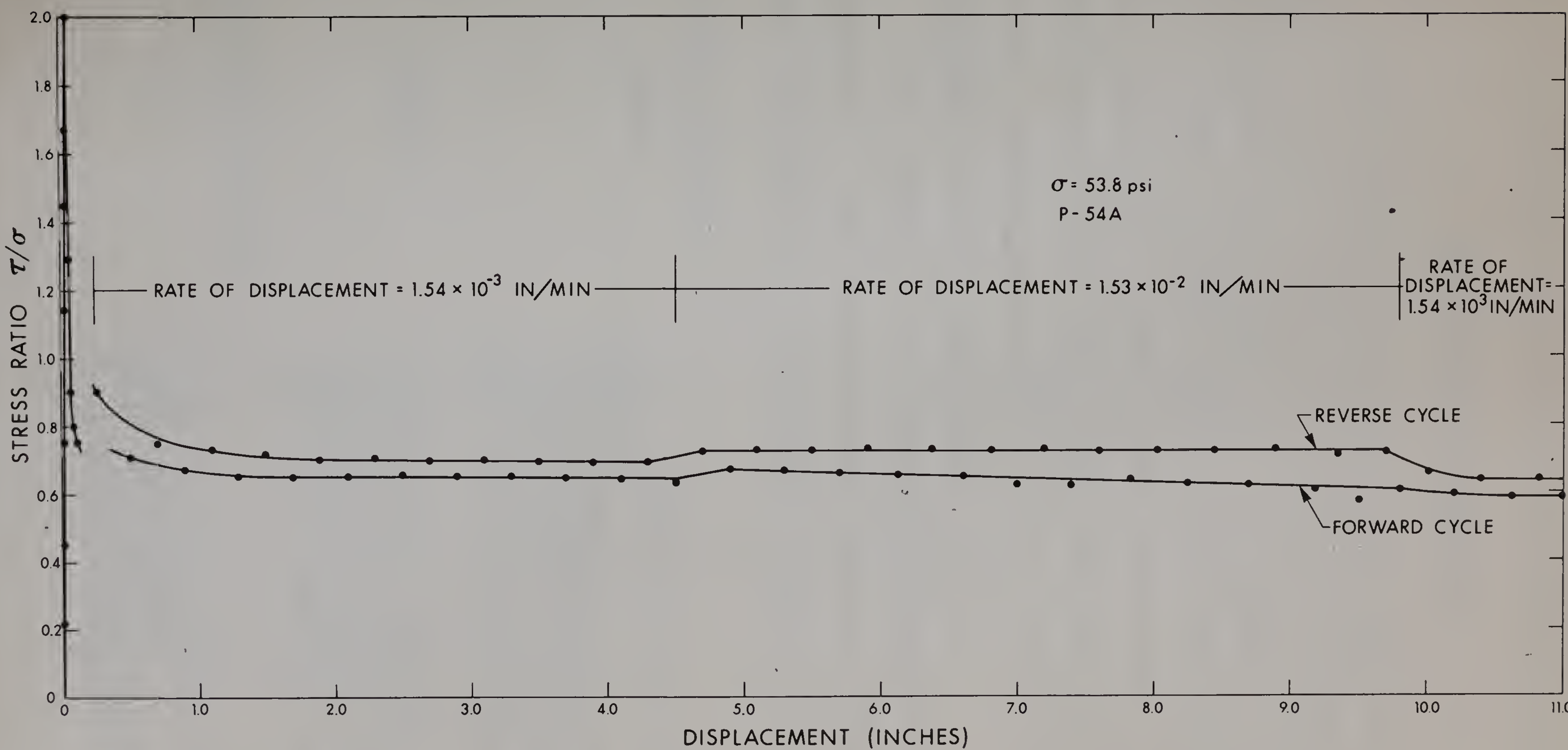


Figure 18

TYPICAL PLOT OF STRESS RATIO VS. DISPLACEMENT

but it is assumed to lie with the different material type.

Direct Shear Results

The results of the direct shear tests on the fine-grained rocks of central Alberta are presented in Table XII and as Mohr rupture lines, Figure 19. The rupture lines were fixed by the method of least squares. (The test results used to establish the Mohr envelopes are plotted for the materials tested by the author but not for the materials tested by previous workers at the University of Alberta (Pennell, 1969; Department of Civil Engineering, 1968)).

As a preface to the ensuing discussions of the shear resistance of the Alberta rocks, the major features of their shear resistance as illustrated in Figure 19 are listed below.

Marlboro Corehole

MRR-45	-peak rupture line #1 statistically correct -peak rupture line #2 ignores data at highest normal load but maybe more representative of strength parameters -very high peak cohesion, 96.6 psi -very high residual (undisturbed) strength
MRR-74	-exceptionally high peak and residual (undisturbed) strength parameters -remoulded and precut samples exhibit comparable strengths but are both lower than the undisturbed case

Entwistle Corehole

P-54	-peak strength results exhibit considerable scatter -high peak strength parameters -residual (undisturbed) cohesion is very high

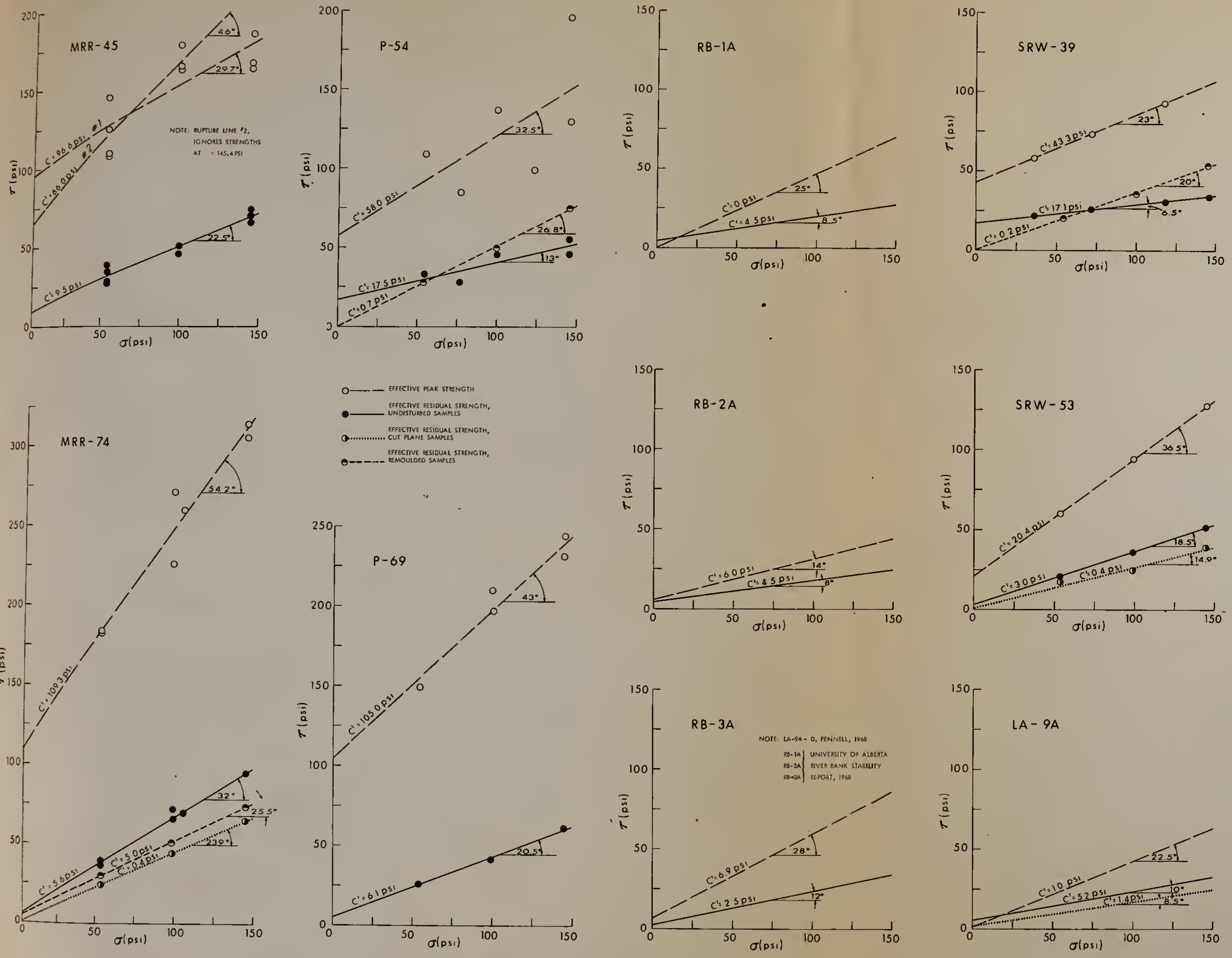


Figure 19

MOHR RUPTURE LINES FOR FINE-GRAINED ROCKS FROM CENTRAL ALBERTA

Entwistle Corehole (cont'd)

P-54	-residual strength of remoulded samples deviates considerably from that of undisturbed material
P-69	-very high peak and residual strength parameters

Edmonton Area

RB-1A	-moderate peak angle of shearing resistance but very low residual angle -residual cohesion is higher than peak cohesion (C_p = 0 psi).
RB-2A	-moderate values of peak and residual strength parameters
RB-3A	-moderate values of peak and residual strength parameters
LA-9A	-residual cohesion higher than peak cohesion -moderate to low values of peak and residual strength parameters

Waskatenau Corehole

SRW-39	-moderate peak strength parameters -residual (undisturbed) cohesion is very high -residual strength of remoulded specimen deviates considerably from that of undisturbed material
SRW-53	-high peak angle of shearing resistance for Edmonton Formation rocks -moderate to high residual angle of shearing resistance

Mechanism of Shear

To deduce the action of shear during a test on natural materials such as the Alberta rocks is a difficult task. Morgenstern and Tchalenko (1967c) noted the mechanism of shear

of remoulded kaolinite by studying a succession of thin sections taken from direct shear specimens interrupted at different stages of deformation. A study of shear action was not an integral part of this investigation, however the following relevant observations associated with the mode of shearing action in the fine-grained rocks were noted.

Measurements of vertical displacement during shear were taken at the beginning of the testing program but were later discontinued. These readings indicated erratic movements of less than a hundredth of an inch in either direction, i.e. expansion or contraction. The movements are attributed to a combination of the following causes:

(1) an apparent expansion or contraction of the sample due to minor variations in sample thickness resulting from uneven grinding during the sample preparation process.

(2) an apparent expansion of the sample due to slight tilting of the direct shear box.

(3) an apparent contraction of the sample because of readjustment of the sample on the upper and lower ribbed gratings. The samples sat on these gratings or set just slightly into them.

(4) an actual expansion of the sample due to dilatency during shear.

Since the readings were erratic and appeared as a result of factors other than internal action of the samples, they were discontinuted therefore the presence of dilatency

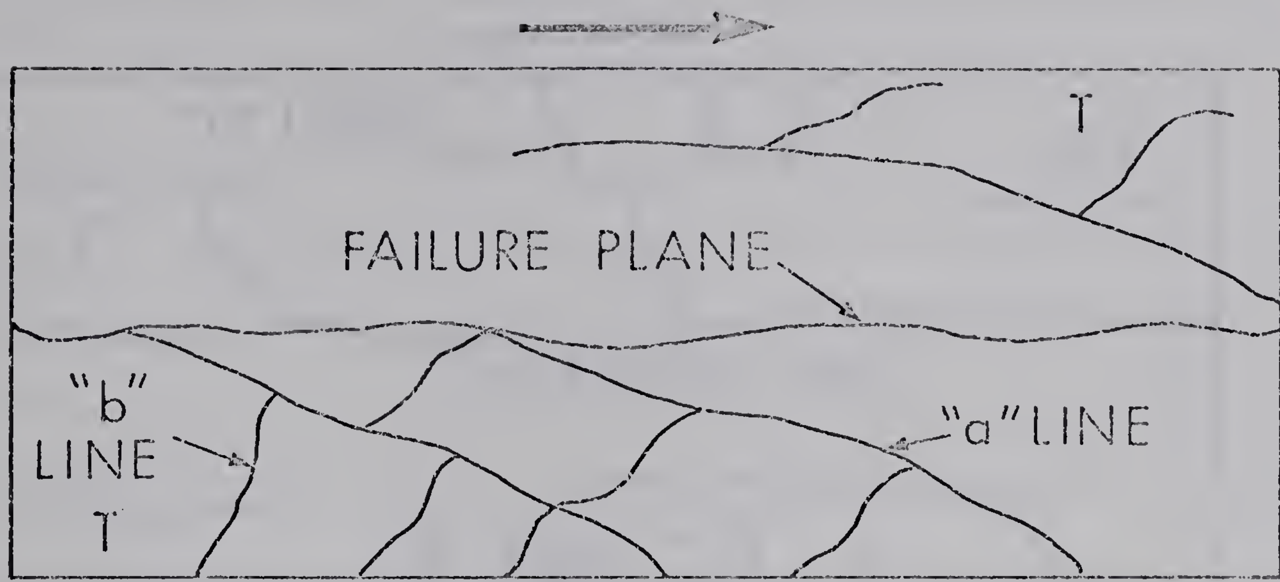
or volume increase during the peak shearing action is not known. Similar inconsistencies in the measurement of vertical displacement have been reported elsewhere (Pennell, 1969; Ali, 1967, per. comm.).

Vertical displacement measurements were more erratic during the reversal technique employed to determine residual strength but these inconsistencies are a direct result of a loss of soil. This loss of material was caused by tilting or upward lifting of the shear box attributed to irregular failure planes and a jacking effect caused by soil or rock fragments collecting between the two halves of the box. In four tests the loss of material was so great that the test was discarded. Removal of the samples at the completion of the test required extreme care to keep the sample intact for subsequent thin-section preparation. In most cases the samples were cracked in what appeared to be a randon fashion and pea-sized fragments dislodged readily along the edges perpendicular to the shear direction. Two samples were so badly broken that their removal resulted in a pile of rubble. These observations are consistent with the following features noted in thin section.

Observations of sample cracking in thin section revealed that two general patterns could be distinguished and these were labelled Type I and Type II cracking patterns.

Type I (Figure 20) patterns have two families of cracks designated as "a" lines and "b" lines. The "a" lines point down from the failure plane against the direction of movement; they leave the failure plane at a low angle, then quickly steepen to an average angle of 20°, and finally intersect the bottom of the sample at an average angle of 30°. A slight change in direction of the "a" lines is often observed where they intersect with the "b" lines. At these intersections the "a" lines may join the "b" lines instead of fully developing. The top half of the sample may exhibit a comparable pattern but it is seldom as well developed as in the bottom half. The "b" lines are usually of a flattened S-shape and are inclined at an average angle of 70° to the horizontal. The "b" lines may cut across "a" lines but normally do not. The Type I cracking pattern is generally found in the more brittle, cemented soft rocks and is best illustrated in the MRR-series, Plate 13, Figures 1, 2, 3.

The Type II cracking pattern (Figure 21) has two families of cracks designated as "c" lines and "d" lines. The "c" lines are horizontal lines found at any location within the sample. The "d" lines are usually of a flattened S-shape and are inclined at an average angle of 80° to the horizontal but may drop to 40°. The "d" lines seldom cut across "c" lines and are more numerous in the central portion of the sample. The Type II cracking pattern is found in the more plastic, compacted, soft rocks with high organic content and is best

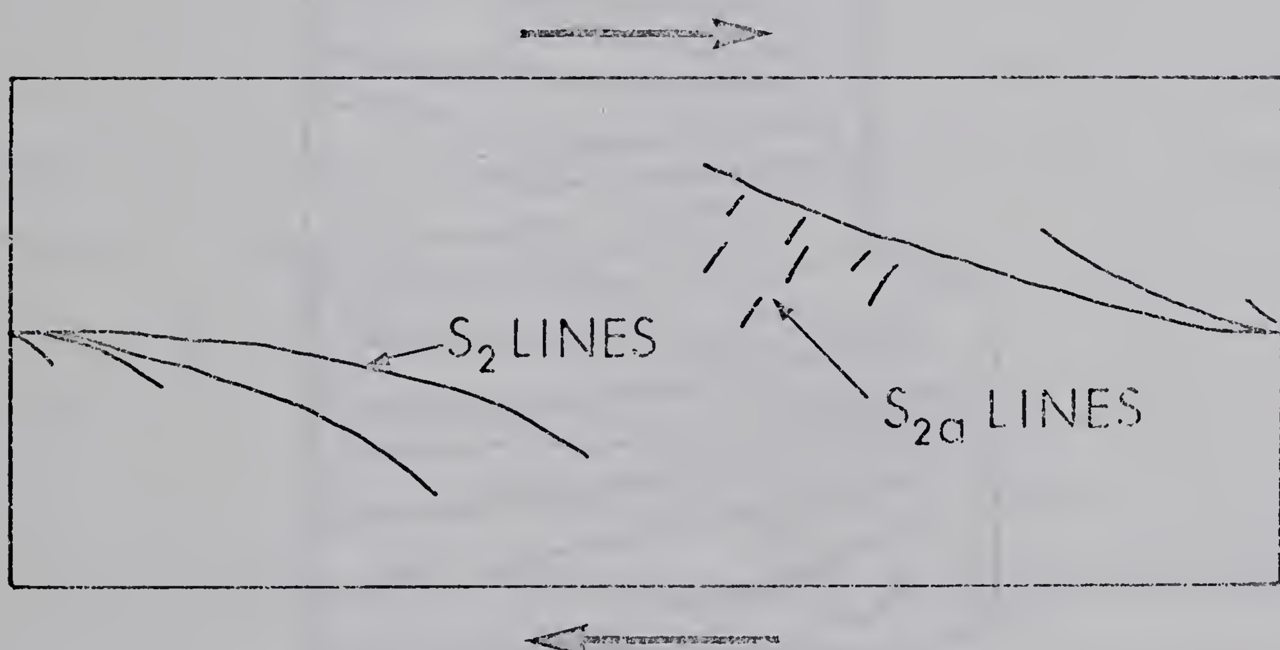


NB: T denotes tension zone

TYPE I

AS OBSERVED IN FINE-GRAINED ROCKS

FROM CENTRAL ALBERTA

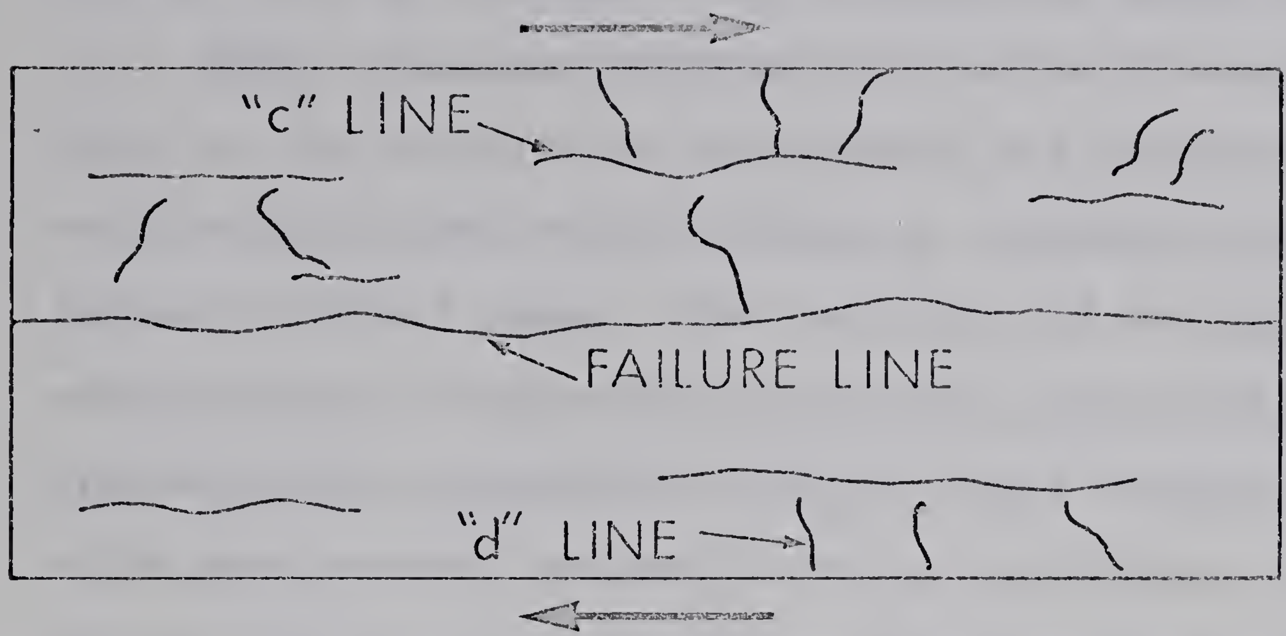


EDGE STRUCTURES: SHEAR PERPENDICULAR TO ORIGINAL FABRIC

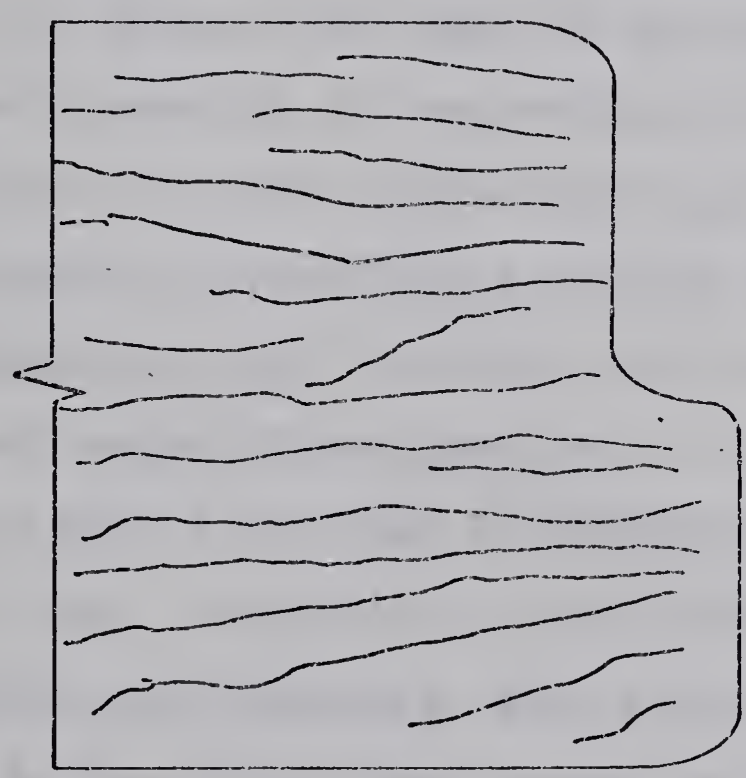
(As reported by Morgenstern and Tchalenko, 1967c)

TYPICAL TYPE I CRACKING PATTERNS

FIGURE 20



TYPE II
AS OBSERVED IN FINE-GRAINED ROCKS
FROM CENTRAL ALBERTA



EDGE STRUCTURES: SHEAR PARALLEL TO ORIGINAL FABRIC
(As reported by Morgenstern and Tchalenko, 1967c)

TYPICAL TYPE II CRACKING PATTERNS

FIGURE 21

illustrated in the SRW-series, Plate 14, Figure 1 and 2.

These cracking patterns will now be discussed in the light of the research by Morgenstern and Tchalenko (1967 c) on microstructures which develop in remoulded kaolinite subjected to direct shear. The "a" lines of the Type 1 cracking pattern appear comparable in attitude and position to the microstructure designated as S_2 in their studies of specimens which were sheared perpendicular to the fabric. They noted that these lines, which are the first features to develop with shear, form a family of cracks which originate at the edge of the box and extend towards the centre (Figure 20).

The "c" lines of the Type II cracking patterns are approximately parallel to the bedding and resemble the pattern of curvilinear discontinuities which produced a slip-line field in samples of remoulded kaolinite with a horizontal fabric (Morgenstern and Tchalenko, 1967 c) (Figure 21).

If both major discontinuities, i.e., the "a" and "c" lines of the Type I and Type II cracking patterns, respectively, are, in fact, comparable to the microstructures noted by Morgenstern and Tchalenko, then their development may be attributed to the high stress concentrations which develop from compression forces exerted by the vertical loading edges of the shear box. The cause of both cracking patterns is attributed to the same factor, but the cracking patterns are different, therefore the properties of the rocks must also be a controlling feature. The "c" lines are approximately

parallel to the bedding, are most marked in strongly laminated soft rocks, and are comparable to slip-lines which develop in those kaolinite specimens sheared parallel to original fabric by Morgenstern and Tchalenko. Therefore, it is tacitly assumed that the horizontal structure, the laminations, control the attitude of the microstructures developed by the edge effects of the shear box. The "a" lines of the Type I cracking pattern occur most markedly in cemented rocks of high silt content which are not laminated and are comparable to the S_2 lines developed in those kaolinite specimens sheared perpendicular to the original fabric by Morgenstern and Tchalenko (1967 c). It appears that the stress concentrations at the edges of the shear box favour the development of microstructures comparable to that of the "a" lines unless there are controlling features, for example laminations and their inherent weaknesses, or other such definite horizontal structures, which cause horizontal microstructures to form.

It should also be noted that the "a" lines appear to develop fully or, at least, to a greater extent than the S_2 lines of Morgenstern and Tchalenko (1967 c). These writers state:

> "Returning to the gross fabric, it is clear that motion along S_2 is impeded by the restraints due to the testing configuration and this is reflected by the lesser development of S_2 towards the mid-portion of the specimen when compared with that towards the edges."

They also state, that in order to accomodate further displacement, rotation of the original fabric must be increased between the S_2 structures to develop new structures. If restraint against motion in the S_2 direction was not developed, slip along this direction would continue, the strength would drop to the residual along this structure, and no new structures would develop (Morgenstern and Tchalenko, 1967 c). With the rocks studied, however, the "a" lines appear to develop fully or, at least, to a greater extent than the S_2 lines. This development may arise because the effective strength of the intact rock is so high that full development of the "a" line is reached before the restraint, as envisaged by Morgenstern and Tchalenko (1967) has developed sufficient stress to form discontinuities of other attitudes. Also, because the rock is cemented, the rotation of the particles between "a" lines required to develop new structures is restrained.

The "b" lines of the Type I cracking patterns appear to be an extension of the S_{2a} lines reported by Morgenstern and Tchalenko (1967 c). It is conceivable that a "b" line is composed of a series of S_{2a} lines which join up to form a flattened S-shape as displacements continue. The "d" lines of the Type II cracking patterns are undoubtably a manifestation of a secondary structure, similar to the "b" lines.

An explanation of the cracking patterns may also lie in the studies of Roscoe (1953). He claims that tension zones occur at the ends of the samples at locations as shown in

Figure 20 and that the cracking associated with such zones appears to develop to a greater extent in more brittle materials. Roscoe also points out that tension is greater when the shear stress exceeds the normal load. It is not known if tension zones do, in fact, occur at these locations in the rocks but the concept may explain the Type I cracking pattern because these patterns are most pronounced in the brittle materials, where in many instances the shear load is greater than the normal load. It may be assumed that the horizontal control by laminations results in "c" lines forming from tensile forces.

These interpretations of the cracking patterns are subject to the following criticisms:

(1) The sequence of crack development is ignored, i.e. it is not known if one "a" line formed completely before another began or if they developed simultaneously.

(2) The effects of shear box reversals on the cracking patterns are not known, i.e., the reversal may have caused the full development of the "a" lines.

Information on these factors is not available at this time.

Morgenstern and Tchalenko claim that simple shear conditions exist in the central portion of the sample and that if only this portion of the failure surface is considered then the ratio:

$$\tau/\sigma = \text{Sin } \phi'$$

(if the cohesion intercept equals zero)

rather than

$$\tau/\sigma = \tan \phi'$$

as is normally accepted.

Where: τ = shearing resistance

σ = normal stress

ϕ' = effective angle of shearing resistance

Despite the tendency for the samples to exhibit cracking patterns comparable to the kaolinite, the normally accepted ratio of stresses ($\tau/\sigma = \tan \phi'$) was employed in this study because, in order to accept simple shear conditions, it must be assumed that no volume change occurs and that edge effects are negligible. Whether or not volume change occurred during the shearing of the soft rocks is unknown, however, it appears feasible to assume such did occur because of the highly overconsolidated nature of the rocks. The cracking patterns indicate that edge effects are significant. Lafeber (1968) suggests, that in a direct shear box of the size employed in this program, the edge effects are very pronounced. Also, insufficient evidence is presented here to make a direct comparison between this research and that of Morgenstern and Tchalenko (1967 c).

The "a" or "c" lines ultimately joined to form failure surfaces which are described as smooth, concave, undulating,

or irregular at the macroscopic scale (Table XIV, columns 2 to 5). The majority of the compacted rocks (Edmonton and Belly River Formations) developed failure planes of a smooth, concave, or undulating nature whereas the cemented rocks (Saunders Group) had mainly irregular failure planes. Further study under the light microscope revealed that these failure surfaces were either smooth or rough. Rough failure surfaces (at the microscopic scale) were generally found with the rocks of high sand plus coarse silt content.

Thin sections revealed failure plane configurations on the two-dimensional basis only, but the feature is three - dimentional as illustrated in Plate 15, Figure 2.

The fracturing of the rocks during shear also developed intact fragments of all sizes and shapes which were termed shear lenses by Skempton (1966). Their occurence is noted in Table XIV, column 9.

Scatter of Peak Strength Results

The scatter of peak shearing resistance test results from the statistically determined Mohr rupture line varies with rock type (Figure 19). In general, the scatter of results is more pronounced in the highly indurated, cemented, rocks of the western portion of the study area, e.g. compare the low scatter of the SRW - series with the wide scatter of the MRR-series. However, such scatter of strength results are to be

TABLE XIV

PETROGRAPHIC CHARACTERISTICS OF FAILURE ZONES IN SAMPLES SUBJECTED TO SHEAR TESTS

SAMPLE NUMBER	MACROSCOPIC: FAILURE PLANE CONFIGURATION				MICROSCOPIC: FAILURE PLANE FACE		WIDTH OF FAILURE ZONE	MATERIAL IN FAILURE ZONE				REMARKS
	Str.	Con.	Und.	Irr.	Sm.	Rou.	Mm.	SHEAR LENSES	REMOULDED MATERIAL: Silt content	Clay orient.	Silt orient.	
1	2	3	4	5	6	7	8	9	10	11	12	
SRW-39A			X			X		X	Some	Nil	Slight	
-39B			X		X		0.5-1.5	X	"	Nil	Slight	
-39R[1]	X				NV		0.75		"	10%	Slight	Silt orientation along secondary cracks; failure plane resealed.
SRW-53A	X					X	0.5	X	Some	Nil	Good	Sample badly fragmented.
-53B				X		X		X	"	10%	Slight	
-53C		Dn			X		0.5-1.0		"	10-20%	Good	
-53D		Dn			NV		1.0		"	Nil	Nil	Failure zone filled with remoulded material.
P-54A			X		X		0.25-1.5	X	Some	10%	Good	25% of failure plane through clay.
-54D			X		X		0.25-0.75	X	"	10%	Nil	
-54G	X				X		0.75	X	"	10-20%	Nil	
-54R[1]			X		X		0.25	X	"	10%	Nil	Failure plane resealed.
P-69A	X					X		X	Some	Nil	Nil	Sample badly fractured.
-69B		Dn			X		0.25-1.5	X	Less	Nil	Nil	
MRR-45A				X		X		X	Less	10%	Nil	Sample badly fractured.
-45B				X		X		X	Some	10%	Good	Sample badly fractured.
-45C				X		X		X		10-20%	Nil	2% of failure plane in carbonates; orientation of clay along border of failure plane.
-45D				X		X		X	(Not present)			Sample badly fractured; distinct failure plane not visible.
-45E		Dn				X		X	Some	Nil	Nil	Most of failure plane removed by thin section grinding.
-45F				X		X	0.5-1.5	X	Less	Nil	Good	
-45G		Dn				X		X	(Not present)			Sample badly fractured.
-45I				X		X		X	(not present)			Sample badly fractured.
-45J				X		X		X	Less	10%	Nil	Sample badly fractured; 2% of failure plane in carbonates; orientation along border of failure alone.
MRR-74B			X			X	0.25-0.5	X	Some	Nil	Nil	
-74C				X		X		X	Less	10%	Slight	10% of failure plane in carbonates; sample badly fractured.
-74D				X		X	0.25-1.0	X	(Not present)			20% of failure plane in carbonates.
-74E		Up			X			X	Less	10%	Nil	
-74F			X		X		0.25-1.0	X	"	10%	Nil	50% of failure zone in carbonates; orientation only in carbonate zone.
-74G			X			X	0.5-1.0	X	Some	10%	Good	25% of failure zone in carbonates.
-74R[1]	X						1.0	X		10%		

[1]R = remoulded samples.

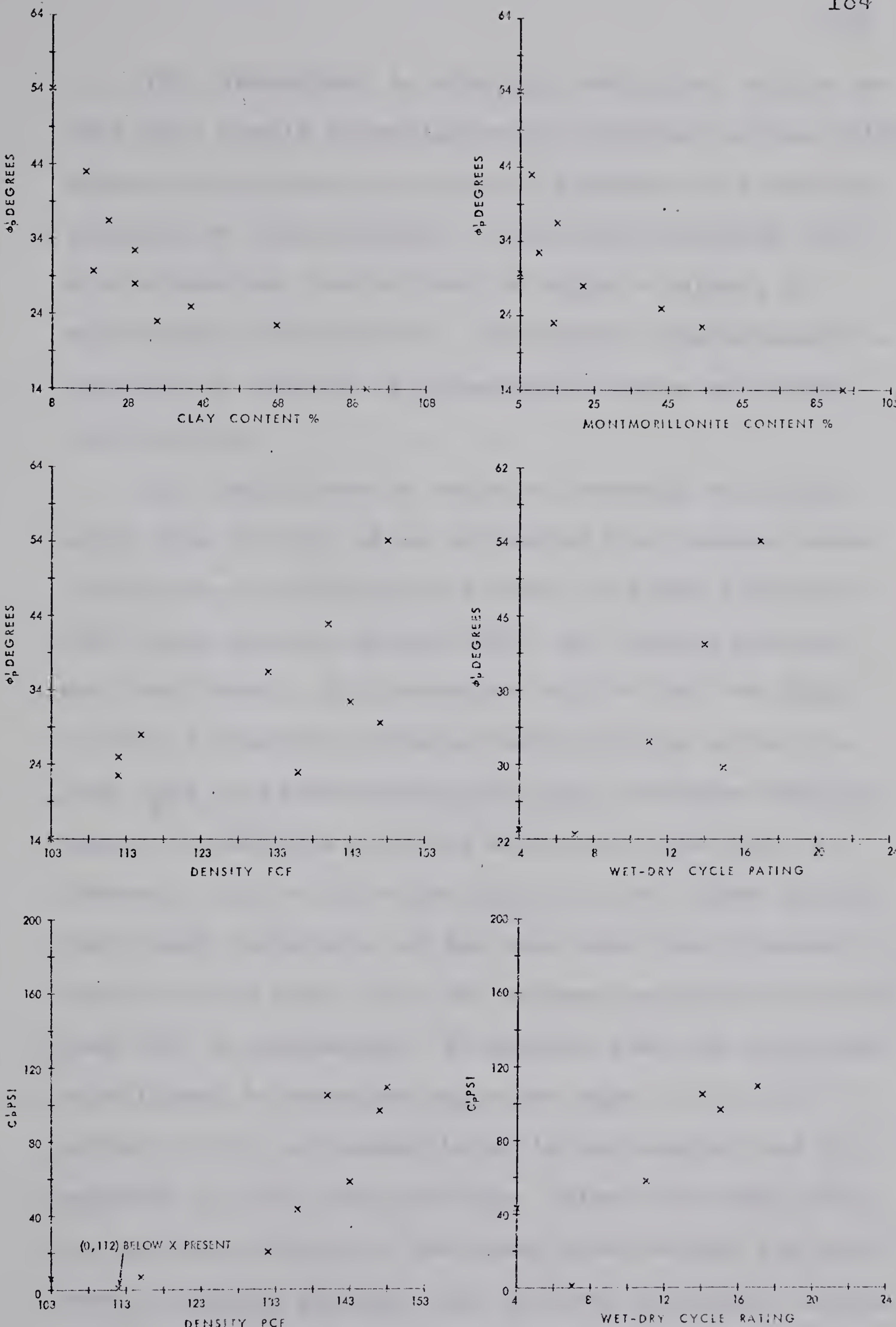
KEY - Col. 2 (Straight): X = present; Col. 3 (Concave): Dn = down, Up = up; Col. 4 (Undulating): X = present; Col. 5 (Irregular): X = present; Col. 6 (Smooth): X = present, NV = not visible; Col. 7 (Rough): X = present, NV = not visible; Col. 8: width measured to nearest .25 mm. unless zone is shattered; Col. 9: X = present; Col. 10: as compared with that of the ambient material; Col. 11 (Clay orientation); Col. 12 (Silt orientation).

expected for natural materials such as rock (Coats, 1965) and, in particular, with sedimentary, fine grained rocks of the types studied, which exhibit wide variations in composition, texture, and structure on the macroscopic and microscopic scale.

A study of the fine-grained rock characteristics of each individual sample with the hope of explaining, in either a quantitative or qualitative manner, the variation of each point from the statistically determined Mohr rupture line was unsuccessful. However, this study did reveal that the following factors influenced the scatter.

(1) Variation in grain size on a macroscopic and microscopic scale (Plate 8, Figure 1) often occurs from sample to sample. A plot of clay content versus the peak angle of shearing resistance, ϕ_p (Figure 22) illustrates the relationship between grain size and strength.

At low clay contents (high silt plus sand contents), such as exist in the rocks from the western portion of the study area, large variations in the peak angle of shearing resistance develop from minor variations in the coarser sized fraction. However, at high clay contents, such as exist in the eastern portion of the study area, minor changes in the peak angle of shearing resistance occur with fluctuations in grain size distribution.



RELATIONSHIPS OF EFFECTIVE PEAK STRENGTH PARAMETERS TO FINE-GRAINED ROCK CHARACTERISTICS

FIGURE 22

(2) Variations in shearing resistance within one rock type result depending on the location of the failure planes with respect to inherent features of structural weakness or reinforcement. Weak zones coincide with micro-fissures, laminations of organic matter, or micro-seams of bentonite. Structural reinforcement is supplied by cements or concentrated zones of recrystallization.

(3) Variations in computed shearing resistance arise from failure plane irregularities because shear resistance calculations are based on plane surfaces. This error appears greater when the failure patterns are considered. If structures such as the "a" lines in Type I cracking patterns fully develop before the peak load is established along some irregular failure plane, the maximum recorded horizontal load will be lowered. If, on the other hand, the "a" lines develop their peak resistance at the same time the irregular failure plane does, then the maximum recorded horizontal load will be increased. It appears that the peak load established is dependent upon the type of failure patterns which are established in the sample, and the sequence in which they develop. Since the rocks from the western portion of the study area develop the most severe cracking patterns and the most irregular failure planes, it is to be expected that they would present

the greater scatter.

(4) Variations in bulk properties such as density and water content undoubtably contribute to scatter, but in most instances they are masked by the previously mentioned factors.

The Mohr rupture lines of two sample series, MRR-45 and P-54, require specific discussion. Sample series MRR-45 shows very wide scatter and two peak rupture lines are shown; rupture line #1 considers all points, but rupture line #2 excludes test results at σ = 145.4 psi. The first line is the best statistical evaluation of the test data and is used in the multiple regression analysis. The second line was established on the weak assumption that all samples at σ = 145.4 psi were poor samples, however, the resulting strength parameters can be shown to improve the relationships with other evaluated parameters (Figure 22) and appear, in the authors opinion, to be more representative of the peak strength of this rock type. However, line #1 must be accepted from the purely statistical point of view as the correct rupture line. It might appear that the rupture line is curved, but curvature has not been reported previously at such low normal loads (Pennell, pers. comm.). Also, a proposed curved envelope would result in a very flat upper slope, flatter by far than the residual angle of shearing resistance ($\phi'_R = 22.5^{\circ}$) which it should approach (Sinclair and Brooker, 1967; Patton, 1966).

Thus, a curved envelope does not appear to be a reasonable assumption.

The P-54 series illustrates that scatter may be attributed to a fluctuation in peak cohesion. Rupture lines may be fitted by least squares to the results (excluding the very uppermost point) to form two other rupture lines, one above and one below the best fit line. The slopes of these lines differ from that of the best fit line by a maximum of one degree, but a variation in the cohesion intercept from 76 psi to 35 psi occurs. This loss in cohesion is attributed to microfissures and structural weaknesses associated with the organic content.

Scatter of Residual Strength Results

The deviations of residual shearing resistance test results from the statistically determined Mohr rupture line are very slight. The major variations are found in the tests on undisturbed samples of rocks from the western portion of the study area. Factors considered to contribute to the scatter are discussed below.

(1) Some variation is expected when dealing with natural samples, particularly when the materials are as heterogeneous as those under study. Variations in grain size and mineralogy which influence the development of residual strength (discussed later) contribute to the scatter of strength results.

(2) The contributions which irregular failure planes and shear lenses make to the development of shear resistance vary from sample to sample thereby causing scatter. These features are more predominant in rocks of the western portion of the study area where the scatter is found to be the greatest.

(3) A portion of the scatter may also be attributed to machine error. The typical stress-ratio versus displacement curve (Figure 18) illustrates a phenomena common to the entire testing program, i.e., the forward shearing displacement produced a smaller limiting stress ratio (residual strength) than the reverse direction. (The forward direction is the direction in which the soil was initially sheared.) To gain an understanding of this phenomena a series of direct shear tests with a range of normal loads were run on Ottawa sand and another series with no soil in the box. In both cases the results were comparable to the tests with the rock samples, that is, the forward motion produced the lower stress ratio. Also, the variation in stress ratio increased as the normal load increased, a feature which was apparent with the rock. From these observations it was assumed that the major portion of the phenomena was due to a form of machine error. The source of this error could not be detected and it was assumed that the average of the two curves should be used to evaluate the minimum shearing resistance.

Statistical Evaluation of Shear Strength Results

The relationships between peak and residual strength parameters and selected petrographic, chemical, and bulk physical properties of the sheared corehole samples are indicated by the corresponding correlation coefficients in Table XV. Unfortunately, the statistical data are based on the analyses of only ten samples, so the conventional level of significance is high, 0.576 at the 5% probability level (Snedecor, 1956). Hence, inferences based on these correlations and on the results of multiple regression analysis described below must be made with caution.

The data in Table XV suggests that the major factors associated with the strength parameters are clay and montmorillonite content, bulk density and related properties, wet-dry cycle ratings, and distance as expressed in miles across the strike of the strata. Examination of plots for each pair of variables shows that some of these relationships are curvilinear and recalculation of the correlation coefficients using logarithmic transformations of clay and montmorillonite percentages and distance shows marked improvement in most of the r values (in brackets in Table XV). Logarithmic transformation of density determinations, however cause little change in the r values, and the relationship of this property to shear strength is assumed to be linear.

TABLE XV

CORRELATION COEFFICIENTS (r) FOR SHEAR STRENGTH PARAMETERS AND OTHER PROPERTIES OF TEN FINE-GRAINED ROCKS FROM THE CENTRAL ALBERTA PLAINS

		COMPOSITION							PLASTICITY				BULK PROPERTIES				DISTANCE
		Clay	Mont.	Ill.	Na	Ca+Mg	P.W.S.	Org.	w_L	w_P	I_P	A	γ_t	e	w_N	W.D.R.	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
PEAK STRENGTH PARAMETERS	ϕ_P'	-.83 (-.94)*	-.72 (-.78)*	-.39	-.26	-.41	-.20	-.26	-.63	-.56	-.63	.15	.73	-.57	-.74	.83	-.53 (-.57)
	c_P'	-.72 (-.82)*	-.67 (-.89)*	.12	-.58	-.26	-.23	-.56	-.70	-.60	-.70	-.20	.87	-.76	-.72	.85	-.77 (-.79)
RESIDUAL STRENGTH PARAMETERS	ϕ_R'	-.72 (-.90)*	-.59 (-.77)*	-.07	-.30	-.31	-.12	-.39	-.56	-.50	-.57	.10	.71	-.56	-.64	.95	-.73 (-.79)
	c_R'	-.15	-.37	.49	-.11	-.35	-.08	.08	-.37	-.55	-.32	-.50	.51	-.34	-.42	-.49	-.04

* Bracketed values determined from log-transformed values of clay, montmorillonite, and distance variables.

KEY – Col. 1: % clay content; Col. 2: % montmorillonite content; Col. 3: % illite content; Col. 4: sodium ion content, milliequivalents; Col. 5: calcium plus magnesium ion content, millequivalents; Col. 6: pore water salts content, millequivalents; Col. 7: % organic matter; Col. 8: liquid limit; Col. 9: plastic liquid; Col. 10: plasticity index; Col. 11: activity; Col. 12: bulk density, p.c.f.; Col. 13: void ratio; Col. 14: % natural water content; Col. 15: wet-dry cycle rating; Col. 16: distance across strike, miles.

Several generalizations can be made from the data in Table XV:

(1) Three strength parameters (ϕ_p', C_p', ϕ_p') exhibit similar correlation patterns with the other rock properties, which indicates that these parameters themselves are closely interrelated. These correlations are:

(a) high with clay and montmorillonite content, density, and related properties such as wet-dry ratings and distance. The relative magnitude of the r values varies somewhat but the signs are the same for each parameter.

(b) moderate with Atterberg limits and plasticity index.

(c) generally non-significant with chemical properties.

(2) The fourth parameter (C_R') shows generally low or non-existent correlations with the other rock properties; correlations with $r = \pm 0.50$ exist with plastic limits and density, which are themselves interrelated (Table VIII). Obviously, either the random technique error associated with the determination is high or this parameter is related to a set of causal parameters, other than those studied.

Multiple regression analysis of some of these relationships were performed with individual strength parameters as the dependent variables and other soft rock properties as independent variables. It must be emphasized that the analysis is based on a small sample size (N = 10) and the interpretation of results therefore must be made with caution.

The multiple regression equation for the effective peak angle of shearing resistance, ϕ_p', is:

ϕ_p' (degrees) = 0.5740 (density, pcf) + 40.2272 (log. montmorillonite content, %) - 61.1377 (log. clay content, %) -0.0466 (log distance, miles) -2.3774

The four independent variables together explain 95 per cent of the variation in ϕ_p' (R^2, Table XVI), but, as indicated by the standard partial regression coefficients (b') distance contributes little to the efficiency of the equation. This is confirmed by deleting the distance factor and recalculating the equation: the R^2 value remains constant (second trial, Table XVI).

In the third trial montmorillonite content is dropped from the equation with a small loss in efficiency (6%), thus it appears that clay content and density are the main factors associated with the effective peak angle of shearing resistance. In fact, clay content alone appears as efficient a predictor of ϕ_P' as the two variables combined, if the difference between R^2 and r_2 values (.89-.88) is taken as a

LINEAR AND MULTIPLE REGRESSION ON (ABOVE) EFFECTIVE PEAK COHESION AND (BELOW) EFFECTIVE PEAK ANGLE OF SHEARING RESISTANCE

TABLE XVI

Independent Variable	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	linear regression
clay content (log.%)	-61.1377	-2.8062	1.00	-61.1432	-2.8065	1.00	-41.2985	-1.8956	1.00	0.8703
density (p.c.f.)	+ 0.5740	+2.2771	0.80	+ 0.5738	+2.2763	0.81	- 0.1340	-0.5316	0.28	0.5341
montmorillonite content (log.%)	+40.2272	+1.5930	0.57	+40.2099	+1.5923	0.57	---	---	--	0.6082
distance (log.miles)	- 0.0466	-0.0030	0	---	---	--	---	---	--	0.3202
a	- 2.3774			- 2.4205			+108.9470			
R^2	0.9506			0.9506			0.8895			

Independent Variable	First Trial			Second Trial			Third Trial			Fourth Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	linear regression
clay content (log.%)	-14.5906	-0.3546	0.12	---	---	--	---	---	--	---	---	--	0.6786
density (p.c.f.)	+ 1.4277	+3.0020	1.00	+ 1.2230	+2.5720	1.00	+ 1.6118	+3.3896	1.00	+ 1.7295	+3.6371	1.00	0.7550
montmorillonite content (log.%)	-28.3672	-0.5957	0.20	-45.7095	-0.9599	0.37	- 5.0355	-0.1058	0.48	---	---	--	0.7891
distance (log.miles)	+15.7317	+0.5365	0.18	+17.1769	+0.5857	0.23	-92.2099	-3.1444	0.93	-93.5339	-3.1895	0.88	0.6222
organic content (%)	-33.9560	-0.4482	0.15	-34.7402	-0.4586	0.18	---	---	--	---	---	--	0.3080
a	-93.3994			-59.6734			+36.4071			+17.8202			
R^2	0.9142			0.9130			0.8813			0.8812			

criterion. Confirmation of clay content as the most important single "contributor" to variation in peak angle is suggested by grouping and analyzing the related data in Table XII by coreholes. In each case, where more than one series of samples was tested (SRW, RB, P, and MRR), the highest peak angle is associated with the lowest clay content, and vice versa. Thus, while some degree of association with density exists, it is masked to a large degree by local variations in clay content.

The multiple regression equation for effective peak cohesion, C_p', is:

C_p' (psi) = 1.4277 (density, pcf) - 14.5906 (log. clay content %) - 28.3672 (log. montmorillonite content, %) + 15.7317 (log. distance, miles) - 33.9560 (organic content, %) -93.3994.

Reference to the corresponding standard partial regression coefficients in trial one, Table XVI, show that density by far is the most efficient predictor of C_p' in relation to the other four variables. However, subsequent recalculations involving successive deletions of the least efficient variable in each case show that distance also contributes to the association with C_p'. Density and distance together "explain" 88 per cent of the variation in peak cohesion, as opposed to either 75 per cent for density or 62 per cent for distance alone. Unlike the inferences derived from multiple regression

analysis of ϕ_P' and ϕ_R', compositional effects appear to be subordinate factors in predicting the behavior of peak cohesion.

The multiple regression equation for the effective residual angle of shearing resistance, ϕ_R', is:

ϕ_R' (degrees)= 44.6365 - 31.7280 (log. clay content, %) + 0.2366 (density, pcf) + 20.1518 (log. montmorillonite content, %) -18.1352 (log distance, miles)

The standard partial regression coefficients, trial one, Table XVII, show that clay content is the most efficient predictor of the effective residual angle, although the other three independent variables appear to play a useful role in this respect. However, subsequent recalculation of the equation and the corresponding standard partial regression coefficients suggest that deletion of density (second trial) and then montmorillonite content (third trial) from the equation leads to only a minor loss in efficiency, about 4.5 per cent; distance and clay content together "explain" 88 per cent of the variation in ϕ_R'. In fact while the standard partial regression coefficients (third trial) suggests that distance is the more important of the two variables, the respective r^2 values for the linear regressions of clay content and distance show that clay content alone "explains" about 81 per cent of the variation in ϕ_R' whereas distance "explains" only 63 per cent. A study of the related data in

LINEAR AND MULTIPLE REGRESSION ON (ABOVE) EFFECTIVE RESIDUAL COHESION AND (BELOW) EFFECTIVE RESIDUAL ANGLE OF SHEARING RESISTANCE

TABLE XVII

Independent Variable	First Trial			Second Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	linear regression
clay content (log.%)	+23.8007	+3.8986	0.54	+23.9983	+3.9309	0.52	0.0010
density (p.c.f.)	+ 0.5142	+7.2759	1.00	+ 0.5358	+7.5816	1.00	0.2559
montmorillonite content (log.%)	- 1.6730	-0.2366	0.03	---	---	--	0.0125
distance (log.miles)	+ 3.4157	+0.7832	0.12	---	---	--	0.0031
a	-98.3480			-96.8178			
R^2	0.7900			0.7825			

Independent Variable	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	linear regression
clay content (log.%)	-31.7280	-2.8048	1.00	-28.0953	-2.4836	1.00	-17.5453	-1.5510	0.82	0.8055
density (p.c.f.)	+ 0.2366	+1.8079	0.64	---	---	--	---	---	--	0.5018
montmorillonite content (log.%)	-20.1518	+2.4928	0.89	+ 8.8041	+0.6726	0.27	---	---	--	0.5961
distance (log. miles)	-18.1352	-2.2433	0.80	-17.4500	-2.1586	0.87	-15.2228	-1.8831	1.00	0.6274
a	+44.6365			+32.2744			+72.3897			
R^2	0.9235			0.9122			0.8778			

Table XII shows that the same relation exists between clay content and ϕ_R' at specific coreholes, i.e., much of the variation in residual angle values can be attributed to local variation in clay content, the effect of which masks regional effects of distance and density. Thus, in the case of both parameters ϕ_P' and ϕ_R' , clay content appears to be the dominant controlling factor.

The multiple regression equation for residual cohesion, C_R', is:

C_R' (psi) = 23.8007 (clay content,%) + 0.5142 (density, pcf) -1.6730 (montmorillonite content, %) + 3.4157 (distance, miles) -98.8480

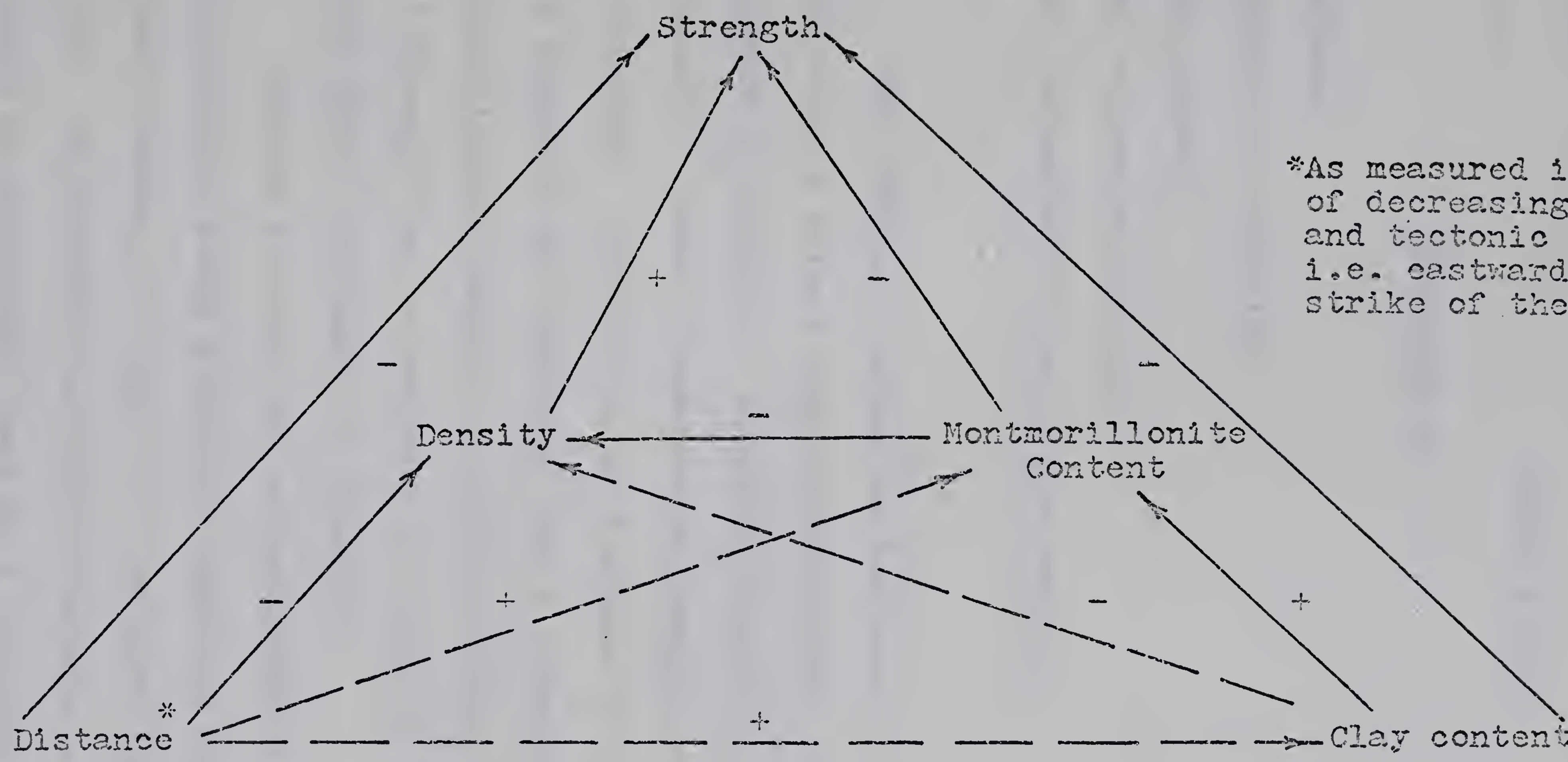
The four independent variables together "explain" about 79% of the variation in C_R', Table XVII, which drops to only 78% when the least two significant contributors (montmorillonite content and distance) are dropped (second trial, Table XVII). The situation is interesting because clay content alone shows a low, non-significant correlation with residual cohesion ($r = -.154$) that can be associated with only 2 per cent of the variation in the parameter. Even density alone is a very inefficient predictor of variation in residual cohesion ($r^2 =$ 0.2559) but the increase in efficiency of the two variables (clay content and density) together appears to have some physical significance. It should also be noted, however, that an increase in clay content is associated with an increase in

C_R', which is contrary to the other strength relationships with clay content. A meaningful statistical interpretation of the "causal" factors associated with C_R' is therefore difficult.

The relationships with respect to effective strength, as outlined above, can be more readily realized with the aid of a schematic diagram (Figure 23). Arrows indicate the sequence of events or effects, and positive and negative signes represent direct and inverse relationships, respectively as determined from Tables XVI and XVII.

The diagram may be explained as follows: distance and clay content are assumed in the light of previous discussion to be the primary "causal" factors in a complex variable system, where distance represents or measures the historical sum of the tectonic and overburden pressures to which the rocks have been subjected during their history, and clay content the basic compositional-textural properties. Density and montmorillonite are secondary factors which themselves are interrelated. All four factors affect "strength" ($\not{O}_P'$, C_P', $\not{O}_R'$, C_R') as discussed above.

In a general manner the effects of increasing distance or clay content on strength are summarized in the following table.



*As measured in terms of decreasing overburden and tectonic pressures, i.e. eastward across the strike of the rock.

SCHEMATIC DIAGRAM OF "STRENGTH" RELATIONSHIPS

FIGURE 23

STRENGTH CAUSAL TABLE

TABLE XVIII

INCREASE IN	STRENGTH
distance	decreases
distance via density	decreases
clay content	decreases
clay via montmorillonite	decreases
clay via montmorillonite via density	decreases

For example, assume an increase in distance. This results in a direct drop in "strength", and a concomitant decrease in density. However, density is directly related to "strength", thus a decrease in density results in a decrease in strength. Similarly, an increase in clay content results in a decrease in "strength" and a corresponding increase in montmorillonite content has two effects: a direct decrease in "strength" and a decrease in density, which is also associated with a decrease in strength.

Similar effects can be postulated if less well-developed relationships among distance, density, clay and montmorillonite contents (shown, in Figure 23 as dash lines) are considered. That is, an increase in either distance or clay content will directly or indirectly lead to a decrease in sample strength dueto the high degree of intercorrelation among the variable

pairs involved. This fact (in conjunction with the small number of samples tested) is the reason for the apparent failure of some of the independent variables to contribute to the precision of the multiple regression analysis of strength and cohesion parameters. One, or at the most, two independent variables are sufficient to predict to "explain" approximately 80 per cent or more of the variation in the dependent variables as summarized in Table XIX.

MAJOR "CAUSAL OR ASSOCIATION" FACTORS OF "STRENGTH"

TABLE XIX

Dependent Variable -Strength Parameter	Independent Variable(s) Capable of Predicting Approximately 80% of the Variation in the Dependent Variable	Percentage Predicted
ϕ_p'	Clay Content	87
C_p'	Density, Distance	88
ϕ_R'	Clay Content	81
C_R'	Density, Clay Content	78

Effective Peak Strength

The effective peak strength of the Alberta fine-grained rocks as determined in the laboratory is dependent upon the properties that the sediment has acquired by heritage and enviroment, and the mechanics by which the strength is evaluated. No attempt will be made to discuss all the basic factors that might be considered to affect peak strength but rather only those which were observed, by means of the statistical analysis and the qualitative petrographic study, to be significant for the particular rock samples tested.

Multiple regression analyses show that clay content is the most important single "contributor" to the variation in the effective peak angle of shearing resistance, ϕ_p'. This relationship is best illustrated on a plot of ϕ_p' versus clay content, Figure 22 (Curves are not presented on these plots because the relationships are not unique in view of other interrelated factors.) At low clay contents (high sand plus silt contents), ϕ_p' drops markedly with an increase in clay-sized material; a drop of approximately 30 degrees may be noted with a corresponding increase in clay content of 25 per cent. With clay contents greater than approximately 35 per cent, there is much less variation in ϕ_p' with changes in clay content the relationship appears to approach and become asymptotic to some ϕ_p' value represented by a line parallel to the clay content axis.

In a general manner, the shearing resistance of soils may be considered to increase with an increase in grain size, i.e., most sands exhibit higher shearing resistance than clays. The effects of the relative percentages of coarse grained particles and clay matrix on shear strength have been studied (e.g. Mitchell, 1956; Trollope and Chan, 1960) but these projects involved remoulded materials, thus the findings are not applicable to the rocks studied and another concept must be found.

With the fine-grained rocks shear occurs either through or around the individual particles depending on the strength of the grains relative to the interparticle bond strength. Generally with the rocks studied, failure occurs around rather than through the sand and silt-sized particles, as they are chiefly quartz, and feldspar which exhibit relatively high strength. However, failure through grains is conceivable, e.g. in a micaceous or clay-sized material bond by a strong cement. Microscopic examination of the failure plane surfaces reveals that the majority of the surfaces are rough or have irregular shaped projections as a result of failure occuring around the particles (Table XIV, columns 6 and 7). These irregularities are most common in rocks of high sand plus silt content. Thus, the surface along which peak strength develops is much like that of a piece of sandpaper with the "grade" dependent upon the grain size of the material. This "sandpaper surface", in turn, is imposed upon the failure

plane configuration (viewed macroscopically) which may be straight, concave, undulating, or irregular (Table XIV, columns 2 to 5).

The development of peak strength appears to be manifested by the development of frictional resistance along the inclined surfaces of all irregularities. Patton (1966) investigated the contribution of irregularities on failure surfaces to strength development by studying the mode of failure of plaster of paris specimens, which had irregularities molded on them. He concluded that the shear strength developed along such irregular surfaces is dependent upon the number, size, and shape of the irregularities. In natural rock specimens the number, size, and shape of the irregularities are unknown. In a general manner, however, it may be assumed that the size and inclination (shape) of the irregularities increase as the grain size increases. The effective peak angles of shearing resistance therefore appear to be related to the clay contents of the fine-grained rocks of central Alberta, at least partially, through the concept of strength development along irregular failure surfaces.

The association of ϕ_p' with the interrelated factors, density, distance, and montmorillonite content (as well as clay content) was previously illustrated in the statistical evaluation. An increase in density of a material results in an increase of shearing resistance, e.g., Kowalski (1966)

found that this relationship could be expressed as a straight line on a semi-logarithmic plot for marls and limestones. The plot of ϕ_p' versus density (Figure 22) exhibits considerable scatter but a trend does exist. It has been shown that an increase in density is associated with an increase in wet-dry cycle rating (Figure 16) which, in turn, can be shown to result in an increase in ϕ_p' (Figure 22). It may be argued in the light of the effect of irregularities on shear strength that an increase in wet-dry cycle rating or, in other words, bond strength should result in an increase in the number and possibly the size of the irregularities, thereby contributing to a strength increase.

An increase in the montmorillonite content results in a decrease in ϕ_p' (Figure 22) as it is associated with an increase in clay content and a decrease in density. It should be noted, however, that a nearly pure montmorillonite sample (RB-2) exhibits a very low ϕ_r' (Figure 19) below the trend illustrated on both the clay content and montmorillonite content (point located at 92%) versus ϕ_p' curves. This example suggests that at higher clay contents the clay mineral type, in particular active minerals such as montmorillonite, exert control over the peak strength developed. Thus, concentrated montmorillonite seams, no matter what thickness, may control the peak strength of a fine-grained rock.

For the purposes of this thesis, cohesion is interpreted simply as the intercept on the shear strength axis. Multiple regression analysis illustrates that two interrelated variables, density and distance, account for 80% of the variation in effective peak cohesion; Cp' versus density, as well as C_p' versus wet-dry cycle rating, is presented in Figure 22. As previously discussed density, distance, and wet-dry cycle rating are strongly interrelated, thus collectively they influence cohesion directly.

The actual factors which contribute to the mechanism of shearing resistance in order to develop the cohesion intercept are unknown, but it appears reasonable to assume that bond strength, as established by cements, et cetera, is a significant factor. Such being the case, wet-dry cycle rating should provide an indication of the amount of cohesion inherent in a fine-grained rock.

In the discussion of the scatter of peak strength results, it was noted that the P-54 sample series exhibited a constant angle of shearing resistance but the cohesion intercept, C_p', varied within wide limits. This variation in C_p' was attributed, in part, to the presence of microcracks in the samples which resulted in a loss of bond linkages and a lower cohesion intercept. Thus, this sample series serves as an example of the effects of bond strength on cohesion.

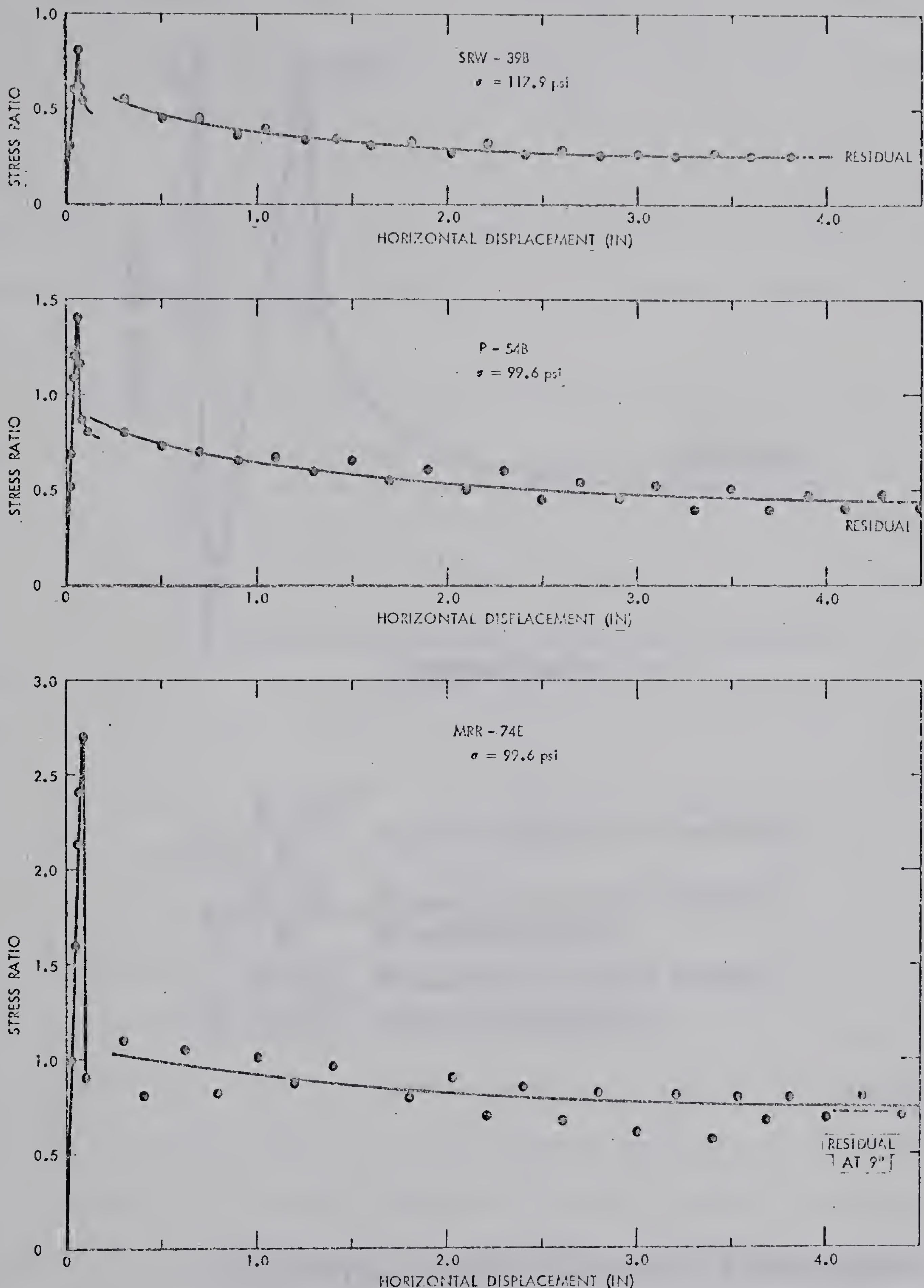
The effects of clay and montmorillonite contents on C_p' appear to be significant only in the way that they in-

fluence density and bond strength (wet-dry cycle rating).

The Reduction of Peak to Residual Strength

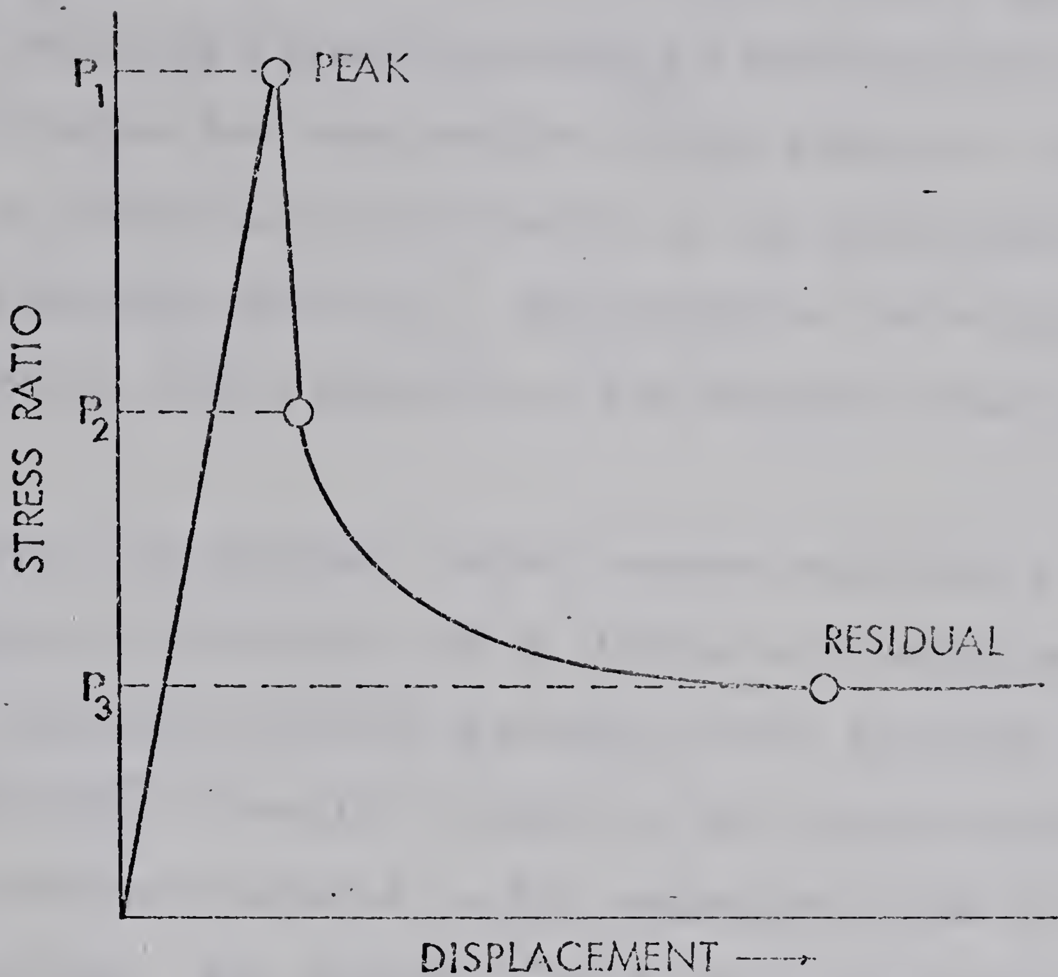
The drop in shear resistance from peak to residual (as defined by Skempton, 1964) generally involves a complete loss of cohesion (the residual cohesion intercepts reported on Figure 19 are discussed later) and what may be a considerable decrease in the effective angle of shearing resistance. The drop in shearing resistance after the development of a peak value differs widely with the Alberta rocks, as illustrated by stress-ratio versus displacement plots (Figure 24). The compacted rocks from the eastern portion of the study area (e.g. SRW-39) exhibit relatively moderate strength drops immediately after peak, followed by a relatively large reduction in strength to the ultimate residual value. The immediate drop in strength after peak is greater with the rocks from the western portion of the area and is followed by a lesser reduction to the ultimate residual value. For example, MRR-74E (Figure 24) exhibits a drastic drop in strength after peak followed by only a slight further decrease to residual strength.

To compare the relative reductions in strength, a series of strength ratios, D_1, D_2, and D_3 (Figure 25) were established. The symbols and ratios are self explanatory except perhaps for P_2; after peak strength is reached the stress ratio drops as a straight line to a point P_2, where it



STRESS-RATIO vs. DISPLACEMENT CURVES

FIGURE 24



$D_1 = \frac{P_1 - P_2}{P_1}$ = % peak strength lost immediately.

$D_2 = \frac{P_1 - P_3}{P_1}$ = % peak strength lost in decrease to residual strength.

$D_3 = \frac{P_1 - P_2}{P_1 - P_3}$ = % decrease to residual strength acquired immediately.

HYPOTHETICAL STRESS-RATIO vs. DISPLACEMENT CURVE TO ILLUSTRATE STRENGTH RATIOS, D_1, D_2, and D_3

FIGURE 25

generally hooks and the rate of strength drop is greatly reduced. Table XX lists the average strength ratio values and their ranges for each sample series studied. The range of D_1 values is attributable to the difficulty in accurately selecting point P_2. The range in the strength ratios occurs because of the scatter of the original shear strength data.

Despite the scatter, which appears relatively wide in some instances, the values of D_1 indicate a definite trend to a greater immediate loss of strength after the peak point with the more brittle, cemented rocks in the western portion of the study area as compared to the compacted rocks of the eastern portion. The values of D_3 indicate how close the material is to the residual strength immediately following the loss of peak strength. For example, MRR-74 series has a D_3 equal to 89 per cent which indicates that a further loss of only 11 per cent of its original strength is required to establish residual strength, however, SRW-39 with a D_3 equal to 33 per cent has to lose 67 per cent more of its original strength to establish residual strength. Thus, D_3 illustrates that the cemented rocks in the western portion of the study area exhibit a shearing resistance nearly equal to residual strength almost immediately after peak strength has been exceeded, whereas the compacted rocks to the east lose only approximately one-third of their competence immediately after the loss of peak strength.

STRENGTH RATIOS

TABLE XX

Sample Series	D_1 %	D_1 Range %	D_2 %	D_2 Range %	D_3 %	D_3 Range %
SRW-39	23	20 - 25	70	68 - 78	33	28 - 37
SRW-53	10	0 - 23	58	55 - 62	17	0 - 37
P - 54	42	32 - 55	68	64 - 71	61	48 - 79
P - 69	63	56 - 67	79	75 - 82	80	75 - 81
MRR-45	53	44 - 59	68	78 - 55	76	72 - 81
MRR-74	67	65 - 63	74	65 - 80	89	84 - 100

This difference in the behavior of the Alberta rocks appears to be mainly attributable to bond type and strength present in the rocks. Bonds were divided into two types by Goldstein and Ter-Stepanian (1957): (a) brittle bonds formed over long periods of time which permit elastic deformation and then fail, and (b) viscous bonds which form, break slowly under stress, and often reform readily. Cementation and recrystallization probably develop the brittle bonds common to the rocks in the western portion of the study area, while electrical attractive forces such as van der Waals and Coulombic forces produce the viscous bonds common to the compacted rocks to the east. Such bond systems may explain the variation between the load-deformation characteristics of the Alberta rocks as they have for clays (Goldstein and Ter-Stapanian, 1957; Crawford, 1963).

Residual Strength from Undisturbed, Precut, and Remoulded Samples

The fact that an appreciable cohesion intercept was obtained in the residual strength determination of undisturbed samples lead to further testing with remoulded specimens and intact specimens with precut failure planes. Residual cohesion intercepts, C_R', ranging from 3.0 to 17.5 psi, were found for the undisturbed rock samples tested by the author and C_R' values of 2.5 to 4.5 psi were found for other rock types in the study area (Figure 19) (Pennell, 1969; Dept. of Civil Eng., 1968; Sinclair and Brooker, 1967).

In fact, the latter studies report values of C_R' greater than C_p', in some instances. The three rock specimens, MRR-74, SRW-53, and LA-9A, tested with precut failure planes exhibited negligible or small cohesion intercepts; values ranged from 0.4 to 1.4 psi. (Only two rock types were tested with cut planes by the author because insufficient samples were available and test preference was given to samples required to establish the peak rupture line.) Residual rupture lines on remoulded specimens also show low C_R' values, i.e., less than 1.0 psi except for MRR-74 which has a $C_R' = 5.0$ psi

The cohesion intercept can, in part, be considered a mathematical entity because its location is often sensitive to the application of least squares to a series of test results. That is, if the scatter of test results was somewhat different, the effective residual angle of shearing resistance may decrease slightly, say by 0.5 to 1.0 degrees, but the cohesion intercept may disappear altogether (or even become negative). With this argument in mind, it appears reasonable to assume that significant values of C_R' occur only for those samples with a high values, e.g., for the undisturbed samples. The remoulded specimens and samples with precut failure planes may be considered to exhibit no cohesion intercept.

What factor establishes the cohesion intercept with the undisturbed samples? Skempton (1964) reported that the residual cohesion for London clay and other overconsolidated clays was so small that it was negligible. With these clays

the increase in water content and orientation of the clay particles has reduced the inherent cohesion such that the material behaves much like a normally consolidated clay. A search of the literature, however, reveals that residual cohesion intercepts may occur because of the influence of irregularities or projections on the failure plane (Goldstein et al, 1966; Patton, 1966; Kenney, 1967).

A study of the failure planes by thin sections and visual examination reveals that in most cases the failure planes which develop in the Alberta rocks have irregularities on both the microscopic and macroscopic scale (Table XIV; Plates 13 and 14; Plate 15, Figure 2; and photographs of failure surfaces, Pennell, 1969). If the cohesion intercept is attributed to strength development along the irregularities of a failure plane, then it appears that it should not be considered cohesion *per se*, but rather as a form of "friction" which is dependent upon the normal stress applied and the weighted mean of the angles of inclination of the projections, in a manner similar to the findings of Patton (1966). The shear resistance developed is a measure of the work exerted by the horizontal thrust to lift and slide each projection past one another, against the effects of the normal load. During the development of the residual strength with displacement (large displacements are acquired by reversing the shearing direction) some projections, which have a strength lower than the stress required move the projections relative

to one another, rupture or break off. In this manner, the shearing resistance decreases with displacement until no further projections break off under the normal load applied and the stress-ratio versus displacement curve levels off. Thus, for these materials the residual shearing resistance found is, in part, dependent upon the normal load applied. A testing program that involves high normal loads might find a residual rupture line with slight downward curvature, reflecting a decrease in resistance with increase in normal load, as a result of the failure of an increasing number of projections. Such envelopes were not found in this program because the magnitude of the normal loads was such that very few projections were sheared off, as shown by the thin section studies.

If the shearing resistance, termed "cohesion", is dependent on the normal stress, then the rupture line should curve downwards near zero normal load and intersect the origin. With this concept, cohesion, as it is generally known, does not exist. In this research program, however, the above concepts are not sufficiently substantiated to conclude the C_R' does, in fact, equal zero at zero normal load therefore the residual envelopes (Figure 19) were drawn in the normal manner.

The statistical evaluation of C_R' showed that clay content and density together were able to account for 78 per cent of the variation in this strength parameter. The effects

of clay content and density on C_R' may be attributed to their influence on the inherent strength of the projections themselves. Fine-grained rocks with a high clay content and low density generally have low bond strength and low shearing resistance. Hence, more projections or irregularities fail in such materials and a low C_R' results.

A comparison of the effective residual angles of shearing resistance, ϕ_R', as determined from undisturbed, precut, and remoulded samples, shows that precut samples have a lower ϕ_R' than undisturbed samples, but that remoulded specimens have ϕ_R' both higher and lower than the undisturbed samples.

Comparisons of residual strength parameters from precut planes to those from undisturbed samples are 23.9° to 32.0° , respectively, for series MBR-74; 14.9° to 18.5,° respectively, for series SRW-53; 8.5° to 10°, respectively, for series LA-9A. The lower ϕ_R' values determined from the samples with precut failure planes are interpreted to be the ϕ_R' values that would develop if the failure plane contained only microscopic irregularities, i.e., the higher values of ϕ_R' determined from the undisturbed samples are in part, due to the irregular failure plane. Whether or not, a direct subtraction of ϕ_R', as determined on precut planes, from ϕ_R', found from undisturbed samples, equals the weighted mean of the angles of inclinations of the irregularities or projections is not known. If the results of Pattons findings on plaster of paris (1966) were applied directly to this research, then this would be the case. However, this particular aspect was not studied in detail in

this program.

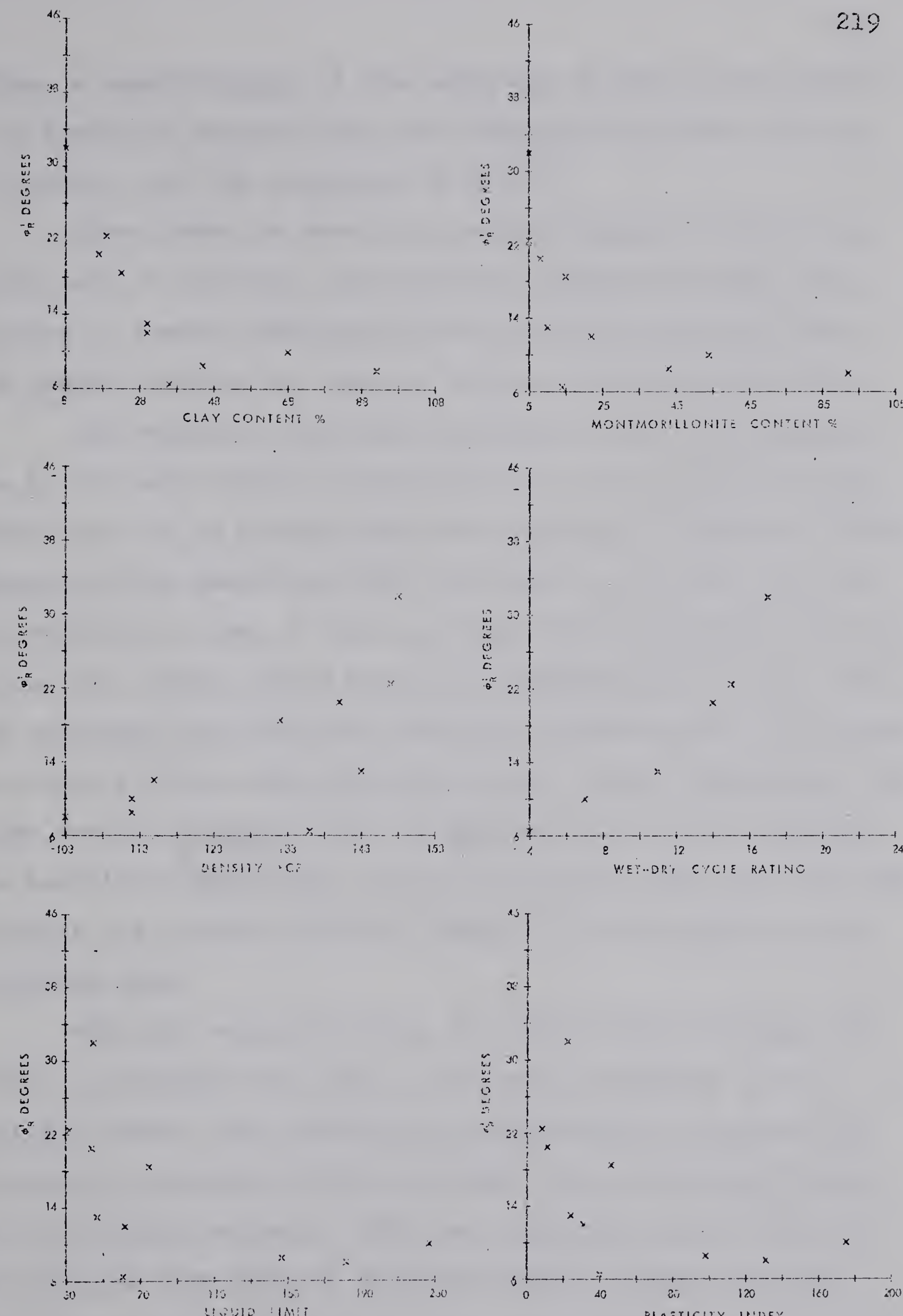
The residual shear strength parameters for the samples with cut planes were selected after a thin skin of "soil mush" had formed between the two halves of the specimen. It was noted that the shear resistance along a freshly cut plane was greater than that which developed after the sample was reversed numerous times and a "soil mush" formed along the cut plane. The frictional resistance between freshly cut surfaces is augmented by microscopic irregularities which are worn off with deformation and the resulting "soil mush" reduces the shear resistance. A similar phenomena was observed by Patton (1966) with tests on plaster of paris.

The ϕ_R' obtained from the remoulded specimen ($\phi_R' = 25.5°$) is very similar to that found on the precut sample ($\phi_R' = 23.9°$) for the MBR-74 series, which for rocks of extremely variable composition and texture may be considered as a reliable measure of the absolute minimum strength for the material. However, the ϕ_R' values from the remoulded specimens for SRW-39 and P-54 (20.0° and 26.8°, respectively) are two to three times their values for undisturbed samples (6.5° and 13.0°, respectively). This latter phenomena was noted by Hayley (1968) in research on the Little Smoky shale.

Hayley (1968) postulated that the variation may be explained by: (a) orientation of clay sizes in undisturbed material as compared to random structure in remoulded specimens, (b) homogeneity of grain sizes in remoulded specimens as com-

pared to laminated grain size distribution in undisturbed samples, (c) segregation of silt and clay sizes in the remoulded material during shear. A study of the thin sections of undisturbed and remoulded samples shows that both exhibited negligible orientation of clay sizes. No consistent variation in the silt content of the remoulded material in the failure zone of either sample type occurred to indicate that segregation of the materials was a contributing factor to the variation in strength. The major contributing factor appears to be the difference in the structure of the specimens, as developed by the distribution of grain sizes.

The undisturbed SRW-39 sample series are laminated and contain less coarse silt plus sand, (as determined by point count) than the homogeneous remoulded sample. The P-54 series are laminated by organic matter and contain finer grain sizes in the organic layers. The remoulded specimen is homogeneous but contains a slightly higher coarse silt plus sand content which is augmented by small, intact pellets of the original material which escaped breakdown. It is difficult to evaluate the effects of lamination in these samples because the original material in which failure occurred was ground up and squeezed out during shear, therefore it cannot be determined if the failure plane was located in a fine or coarse grained lamination. As indicated by Figure 26, a small increase in the coarse-grained content of the Alberta rocks can contribute to a significant increase in the value of ϕ_R'



RELATIONSHIPS OF EFFECTIVE RESIDUAL ANGLES OF SHEARING RESISTANCE TO FINE-GRAINED ROCK CHARACTERISTICS

FIGURE 26

Thus, a consideration of the variation in grain size between the remoulded material and the undisturbed material appears to account for the variation in ϕ_R'.

These tests on remoulded material suggest that it is difficult to estimate the effective residual strength parameters of complex materials such as the fine-grained rocks of central Alberta by means of test on remoulded specimens.

The multiple regression analysis showed clay content to be the major factor contributing to the variation in ϕ_R', which fact is in keeping with the findings of Skempton (1964). Skempton also postulated that the drop in strength from peak to residual is due, in part, to the increase in water content along the failure plane and to the development of thin bands of oriented clay particles along the failure plane. He points out that silt or sand particles do not orient themselves, thus they exhibit a higher value of ϕ_R' and where coarse material is associated with clay, the ϕ_R' is greater than for clay alone because the coarser material inhibits the development of an oriented band.

With the cemented rocks, the major factor causing the drop in strength from peak to residual is rupture of the brittle bonds; this occurrence is followed by a further reduction in strength due to the break down of irregularities on the failure surface. With the compacted rocks, the loss of strength from peak is somewhat similar except the bonds are viscous and their rupture does not involve such a drastic

initial loss of strength. The effects of water content on the failure surface are unknown (the samples had to be kept intact for thin section studies), however, it appears reasonable to assume that the water content could be a significant factor only with the compacted rocks, as the cemented soft rocks appear to lose nearly all their peak strength with bond rupture and breakdown of irregularities on the failure plane.

Thin section studies of the failure planes of the rocks tested both in this research and that of Pennell (1969) failed to reveal oriented clay bands, even in those samples which were predominantly clay sizes. The lack of particle orientation may be attributed to: (a) the high silt and sand content, as previously suggested by Skempton (1964), (b) the strong interparticle bonds which prevent orientation of clay particles, (c) the numerous irregularities on the failure surface which act as "mixers" during the shearing operation, thus preventing particle alignment. Of the three suggested reasons, the latter appears to be the most significant, because in many cases there was sufficient remoulded material in the failure zone to orient unless some action such as mixing prevented it.

Since particle orientation appears insignificant in the development of the residual strengths of the Alberta rocks, the contribution of clay content to ϕ_R' must be of a different nature than that suggested by Skempton (Figure 26). The influence of clay content on residual strength is believed to lie once again with the contribution to shear resistance of

irregularities of either macroscopic or microscopic size. The residual angle of shearing resistance, for example, on a precut plane, will decrease as the microscopic irregularities decrease, i.e. as the particle size decreases or the clay content increases. With relatively larger irregularities the increase in clay content is associated, for the Alberta rocks with a decrease in density and interparticle bond strength, hence an increase in the number of fractured irregularities and a corresponding decrease in ϕ_R' (Figure 26).

Kenney (1966) investigated the influence of mineral composition on the residual strength of natural soils and fabricated soil systems and concluded (for his soil systems):

> "The results that have been obtained indicate that the residual strength of a soil is dependent on mineral composition and system chemistry (that is, composition of the pore fluid and the types of ions adsorbed on the mineral particles), but is not necessarily dependent on, or reflected by, the grain size or plasticity characteristics of the soil".

The plots of ϕ_R' versus montmorillonite content (Figure 26) show only a slight tendency for a relationship between these two factors and the statistical analysis illustrates that any effect that montmorillonite content might have on the ϕ_R' values of the Alberta rocks is masked by the influence of clay content. The salt contents of the fine-grained rocks do not appear to influence ϕ_R', but the salt types and contents are not known spearately for the adsorbed and electrolyte states.

Attempts have been made to relate plasticity to residual strength (Sinclair and Brooker, 1967; Kenney, 1966). Kenney's work indicates that even for pure soil systems an unique relationship between plasticity and ϕ_R' does not exist. His plot of plasticity index versus the tangent of ϕ_R' shows a tendency for a decrease in residual strength with an increase in plasticity, but there is considerable scatter. Plots of liquid limit and plasticity index versus ϕ_R' for the Alberta rocks (Figure 26) show a tendency for a decrease in ϕ_R' for an increase in plasticity, but a definite relationship does not exist. Thus, despite the fact that such factors as clay content, mineralogy, and systems chemistry have been related to ϕ_R' by various workers and the fact that each of these factors also affects plasticity, any relationship between plasticity and ϕ_R' appears too weak to evaluate ϕ_R' of a material based on a knowledge of its plasticity.

CHAPTER VIII

DIAGENESIS

In the transformation of sedimentary deposits to rock, the mass passes through a phase which does not exhibit in its entirety the characteristics generally accepted as being associated with either a true "rock" or "soil", as discussed in Chapter I. This phase, called here the transitional or "soft rock" phase (the grey zone), is believed to be represented in the near-surface bedrock formations of central Alberta. The geotechnical properties of these soft rocks have been discussed with reference to the associated petrographic properties and regional geologic context of the strata, and it is worthwhile here to attempt to relate these properties to the effects of post depositional (i.e. diagenetic) processes involved in the soil-rock transformation. For the purposes of this study diagenesis is considered to be the net effect of four processes: compression, chemical alteration, cementation, and recrystallization. It is generally recognized that the complexity of these processes inhibits separating their effects into well-defined, measurable entities (Krumbein, 1942), but the sum or mass effects can be detected or inferred in many cases. An attempt is made to do this in the ensuing discussion, which involves the following topics:

(1) factors influencing diagenesis;

(2) the effects of diagenetic processes upon the properties of the sediments;

(3) geotechnical properties as indicators of diagenetic effects.

Factors Influencing Diagenesis

Factors influencing diagenetic processes are:

(1) initial texture and composition of the raw detritus;

(2) geochemical factors such as pH (hydrogen ion concentration), Eh (oxidation reduction potential), pore water composition;

(3) pressure-temperature conditions during and especially after deposition.

During and immediately after deposition, the unconsolidated clastic material (soil) is subject to mineralogical and textural changes that strive to attain an equilibrium between the detritus, the composition of pore fluids, and the surrounding physico-chemical environment. In cases where the detritus contains a high proportion of "unstable" constituents (e.g.feldspars, volcanic glass), such as the Cretaceous-Tertiary formations of central Alberta, the bulk sediment is particularly prone to breakdown with the concomitant formation of minerals stable at normal temperatures and pressures; clay minerals (especially

montmorillonite and kaolinite), carbonates, sulphates, opal, iron oxides, _et cetera_.

Texture also plays an important role, governing the initial porosity and permeability of the wet sediment. Krumbein (1942) states:

> "From these and other sources it appears that freshly deposited sand contains about 45 per cent water, silt has 50 to 65 per cent, and mud (clay) has from 80 to 90 per cent. Colloids (under 1 micron) have about 98 per cent water at the time of deposition."

Thus, finer-grained sediments have a greater chance to undergo chemical-mineralogical changes, both because of their more active nature (larger surface area per unit volume) and because of their higher porosity, e.g. a higher porosity leads to a greater percentage of chemical constituents available for reaction in the pore water.

Geochemical conditions in the basin of deposition are determined by a number of factors including sediment composition, basin topography, rates of deposition, temperature, _et cetera_. The pH and Eh of the depositional medium are particularly influential in determining the initial course of chemical reactions in the unconsolidated sediment. The initial chemical changes that take place in the newly deposited sediment may have considerable bearing on the subsequent (diagenetic) course of events.

Finally, the effects of physical agencies (pressure, temperature) associated with the various stages of burial and subsequent uplift must be considered. These stages are for the

Alberta rocks:

(1) compression under an original overburden load of several thousand feet;

(2) horizontal compression and uplift under the influence of thrust forces associated with Laramide mountain building;

(3) rebound associated with post-Laramide uplift and erosion of several hundred to several thousand feet of sediments;

(4) compression and rebound associated with Pleistocene glaciation.

Apart from influencing the chemical-mineralogical equilibrium of the beds, these agencies effect certain changes in the bulk physical properties of the rocks, including their geotechnical properties. Thus, although the geologic stress history of the study area is quite complex, and its results are not known in detail, some of the derived effects associated with diagenesis (and the reverse process) can be related to certain events.

Influence of Diagenesis on Sediment Properties

Composition

Obviously, the processes of chemical alteration and cementation strongly affect the bulk composition of a sediment whereas compression and recrystallization contribute only indirectly. Cementation may involve adding new material to

the clastic constituents (e.g. carbonate cement to a quartz sandstone), and chemical changes in the constituents, either detrital or authigenic, already present in the rock. Naturally, the amount and type of adsorbed and pore water salts of the sediment may be radically affected by these processes.

Petrographic studies of the nonmarine Cretaceous-Tertiary rocks of central Alberta suggest that two series of compositional changes associated with diagenesis have taken place (Carrigy and Mellon, 1964):

(1) initial alteration of unstable volcanic detritus (glass, feldspars, micas) to form montmorillonite and kaolinite, which are found as "cements" in the sandstones; and

(2) subsequent upgrading or "metamorphism" of montmorillonite and kaolinite to illite and chlorite under the influence of heat and pressure in the Foothills region.

Although Carrigy and Mellon's observations were confined to studies of sandstones, similar compositional changes may be expected in the finer-grained rocks, such as those described in this report. In fact, there is some indication that the illite/montmorillonite ratio increases as the Foothills are approached, although montmorillonite can and does exist within the folded belt.

Texture

Recrystallization is responsible for the "joining" together of grains to form larger grains of different shape. The influence of recrystallization on grain packing and orientation may be considered negligible, if it is assumed that recrystallization becomes significant late in diagenetic processes after grain readjustment is complete.

Chemical alteration will change grain size and shape markedly as coarser-grained clastic material alters to fine-grained clay minerals (for example, the alteration of volcanic glass fragments to montmorillonite). Changes of grain size and shape also may be expected within the fine-grained constituents because these materials are the most susceptible to such processes as chemical alteration. The influence of chemical alteration on grain packing and orientation is mainly restricted to those cases in which alteration occurs before the sediments have ceased particle readjustment, e.g. alteration of montmorillonite from volcanic ash may occur during early diagenesis, forming an oriented texture (Plate 2, Figure 2), whereas alteration from relatively larger volcanic glass fragments may take place at such a late stage that orientation of the individual montmorillonite grains (or aggregates) is impossible (Plate 5, Figures 1 and 2).

Cementation can alter grain size and shape in those cases in which cements replace portions of the constituents of an original grain. Cementation can, of course, influence

the results of grain size analysis for the cements will hinder the breakdown of a fine-grained rock mass into primary particles. Its effect on grain packing and orientation is significant only if the cementing action occurs before grain readjustment and compression are complete and if the cement linkages are capable of resisting the compressive forces.

Compression may cause particle degradation and hence changes in grain size and shape, but its major influence is on grain packing and orientation. An increase in compressive forces will lead to tighter packing arrangements; it is generally argeed that minerals with a large ratio of surface area to thickness favour orientation under load (Morgenstern and Tchalenko, 1967c). The preference of small pockets of montmorillonite to exist in a highly oriented state in the Alberta rocks may support this point of view.

Structure

Large scale structures may be induced in sediments by compression, e.g. draping of shale beds over a reef by differential compression of the shale. Similar features also might be expected on a smaller scale. Cementation, recrystallization, and chemical alteration are significant in that they affect compression and the formation of "induced" structures such as fissures.

Plasticity

The plasticity of a fine-grained deposit will be affected mainly by those diagenetic processes which influence composition, e.g. chemical alteration and cementation. Certainly, the alteration of pyroclastics to montmorillonite is an outstanding example of the effects of diagenesis on plasticity. Processes which alter the ion system will affect plasticity in accordance with the activity of the clay mineral and ion complex.

Cementation and recrystallization will influence the plasticity indicies as determined in the laboratory by affecting the total surface area per unit volume which must be sufficiently hydrated to develop the liquid and plastic states.

Bulk Properties

All four diagenetic processes will affect the bulk or mass properties (density, wet-dry cycle ratings, etc.) of sedimentary rocks to some degree.

The effects of compression on bulk properties was presented in foregoing sections. The moderate influence of chemical alteration on bulk properties is attributed to the active nature of clay minerals, in particular montmorillonite; these alteration products resist compression and hence exhibit high void ratios, high water contents, and low densities because of their affinity for water. These materials are also susceptible to breakdown readily in wet-dry cycle tests.

Cementation and recrystallization have a minor effect on density, water content, and void ratio by virtue of their ability to hinder compression. Thus, they may lead to higher void ratios, higher water contents and lower densities. However, cementation also may exhibit the opposite effect, i.e. the infilling of a cement in a void will reduce void ratio and water content, and increase density. The magnitude of the resultant effect is unknown but it is sufficient here to recognize that cementation and recrystallization do influence the bulk properties mentioned above to a minor degree. The highly significant effect of cementation and recrystallization on wet-dry cycle ratings is readily apparent in view of the fact that both of these processes increase bond strength.

Effective Shear Strength

All four diagenetic processes may be considered to affect the effective peak strength parameters because each process is instrumental in the development of bonds within the soft rock mass. Bond strength is directly related to cohesion and to the development of the angles of shearing resistance through the concept of "irregularities".

The effective residual angle of shearing resistance is influenced mainly by chemical alteration in view of the fact that clay mineral content is a major "contributor" to this parameter. Compression, cementation, and recrystallization have a moderate influence on the residual angle as determined

on undisturbed samples because these processes affect the presence of "irregularities" on the failure plane. However, the influence of diagenetic processes on the effective residual cohesion is uncertain.

Summary Table

The effects of diagenetic processes on the properties of sedimentary rocks is summarized in Table XXI, modelled after a similar table presented by Krumbein (1942). In cases where the proposed effects agree with those of Krumbein, an asterisk is employed to indicate agreement.

The table is intended to serve as a rough guide for qualitatively estimating the changes which take place in a sediment during the transformation from a soil to a rock. For example, if the study of the geologic history of a soft rock mass indicates that compression has been the major operating diagenetic process, then it is to be expected that the bulk properties and shearing resistance parameters have undergone major changes due to the processes of diagenesis. On the other hand, if chemical alteration is the major operating diagenetic process, then likely all the original properties of the sediment have altered. In a similar manner, the table may be useful to indicate which diagenetic processes may have occurred on the basis of a study of the geotechnical proper-

RELATIVE EFFECTS OF DIAGENESIS ON SEDIMENT PROPERTIES

TABLE XXI

Geotechnical Property	Diagenetic Process			
	Compression	Cementation	Recrystallization	Chemical Alteration
Composition				
silt and sand	---	XX	---	XX
clay minerals	X	XX	---	XXX
organic matter	---	---	---	XXX
adsorbed salts	---	XX	---	XX
pore water salts	---	XX	---	XX
cements	X	XXX	---	?
Texture				
grain size	X	X*	XXX*	XXX*
grain shape	X	X*	XXX*	XXX*
grain packing	XXX	XX	---	XX
grain orientation	XX	XX	---	XX
Structure	XX	X	X	X
Plasticity	---	X	XX	XXX
Bulk Properties				
water content	XXX	X	X	XX
void ratio	XXX	X	X	XX
density	XXX	X	X	XX
wet-dry rating	XXX	XXX	XXX	XX
Effective Shear Resistance				
peak cohesion C_p'	XXX	XXX	XXX	XXX
peak angle, ϕ_p'	XXX	XXX	XXX	XXX
residual angle, ϕ_R'	XX	XX	XX	XXX
residual cohesion C_R'	?	?	?	?

Legend:
X - minor effect
XX - moderate effect
XXX - major effect
--- negligible effect
? - unknown effect
* - also suggested by Krumbein (1942)

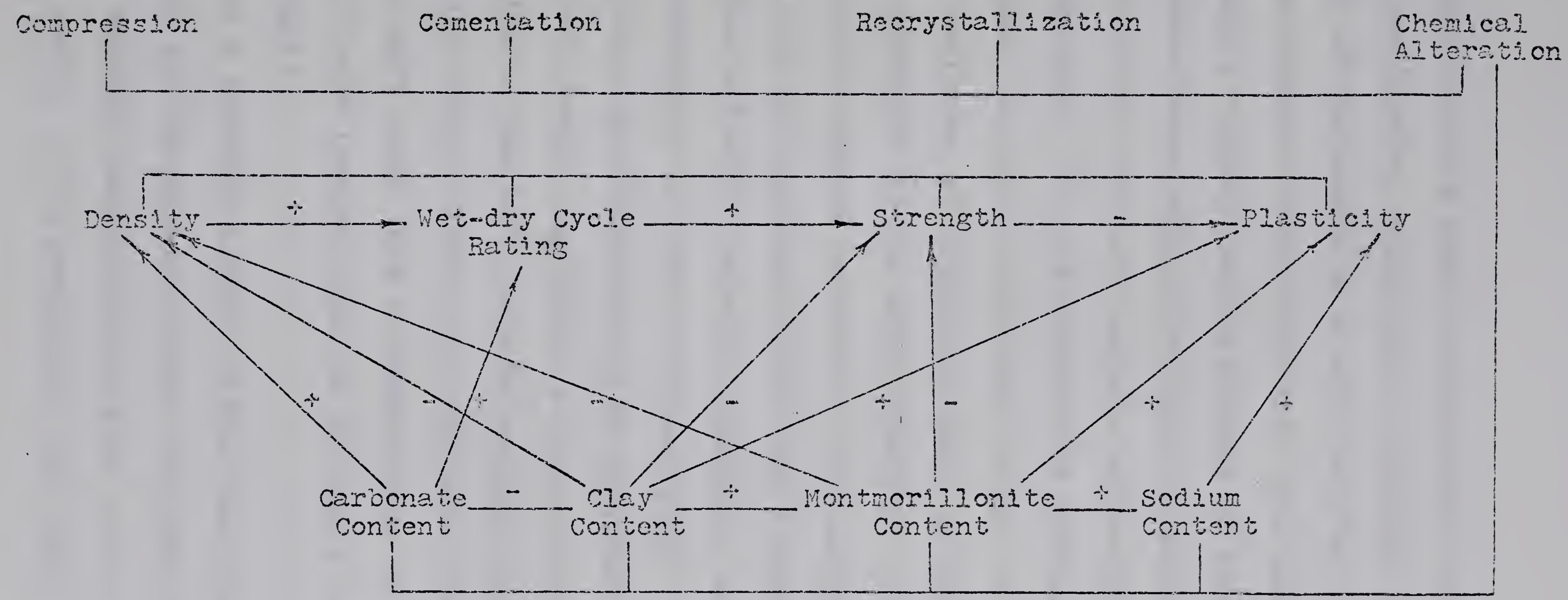
ties of a sediment.

Schematic Diagram

A schematic diagram which illustrates the major effects of the diagenetic processes on the interrelated geotechnical properties of the soft rocks of central Alberta is shown in Figure 27. The diagram is an attempt to tie together the significant features of similar "cause and effect" diagrams and related them to the diagenetic processes. The diagram is self-explanatory in the light of examples provided for previous schematic diagrams.

Geotechnical Properties as Indicators of Diagenetic Effects

The geotechnical properties of the soft rocks of central Alberta appear to exhibit wide variation in engineering properties across the study area, as illustrated by the decrease of propensity for slope failure along the bedrock river valleys in a westerly direction. The gross lithology and inferred depositional origin, however, remain similar over this distance and it is postulated that diagenetic processes contributed to the variation in geotechnical characteristics of the rocks. Discussion of geological effects on the engineering and petrographic characteristics appears to substantiate the above postulation, i.e., diagenesis should be considered as a major "contributor" to the development of the engineering properties of the soft rocks. If the significance of diagenesis is



SCHEMATIC DIAGRAM TO ILLUSTRATE THE MAJOR EFFECTS OF THE DIAGENETIC PROCESSES ON INTERRELATED GEOTECHNICAL PROPERTIES OF THE SOFT ROCKS OF CENTRAL ALBERTA

FIGURE 27

accepted, then it would be beneficial to have some parameter, even qualitative, which can be employed to evaluate the net effect of diagenesis on a soft rock, so that such materials may be compared with one another on a common basis. An attempt to place a "rating" on the process of diagenesis may appear premature, especially since there is neither a precise definition of the term nor complete comprehension of the processes. Nevertheless,, in the interest of eventually developing such a system, the writer advocates the use of wet-dry cycle tests as an indicator of diagenesis based on the supposition that "bond strength" is the major "product" of diagenesis. This supposition appears reasonable, for the generally accepted definition of diagenesis infers the production of a "rock" mass from a freshly deposited sediment, and in such a process the development of bonds certainly plays a major role. Thus, the wet-dry cycle ratings may be considered to evaluate, at least relatively, the extent to which diagenesis has been effective in the soft rocks of central Alberta. As the wet-dry cycle ratings (Table III) indicate, the majority of the studied soft rocks form a "transitional or grey zone" between a true "rock" (rating equal to 20) and a true soil (rating equal to 1).

In a previous section titled "Soil-Rock Transformation", (Chapter II) the question arose- "At what point in the system does a material cease behaving like a soil and begin behaving like a rock"? It is recognized that there is no sharp line of

demarcation between true "soil" and "rock" rather, as has been suggested in this report, an intermediate zone of material with gradually changing characteristics exists. However, it is conceivable that at some point or stage in the transformation the behavior of soft rock may be accepted as weighting more heavily towards a "rock" rather than towards a "soil". Such a point was selected only on the basis of changes in material behaviour occurring consistently at approximately the same point; this point maybe defined by a wet-dry cycle rating of eleven. Changes in material behavior which were noted to occur at this point are as follows:

(1) cementation rocks occur at wet-dry cycle ratings greater than eleven, and compaction rocks at ratings of eleven and lower, as interpreted from Philbrick's definition (1950);

(2) those soft rocks with wet-dry cycle ratings of eleven or greater exhibit a large drop in shear resistance after peak strength is exceeded; thus, they demonstrate a more brittle nature (rock-like) than the materials with ratings of eleven and lower which are more viscous in behavior (soil-like);

(3) those soft rocks with a wet-dry cycle rating of eleven or greater exhibit large cohesion intercept values which indicate a high intrinsic strength at zero normal stress;

(4) wet-dry cycle ratings of eleven or greater occur in most of the soft rocks west of the Pembina River, which border coincides with a considerable decrease in the propensity for river bank instability.

As the above factors indicate, the point or boundary between those materials which appear to be more "rock-like" or "soil-like" coincides with the chosen boundary between cemented and compacted materials, or, in other words, cemented rocks may be considered "rock-like" and compacted rocks "soil-like" in a relative sense. Others have noted that cemented and compacted rocks differ in aspect when employed as foundation materials. Mead (1936) observed that, upon exposure to the atmosphere, compaction rocks disintegrate rapidly when subjected to wetting and/or drying, whereas cemented rocks have considerable resistance to the weathering action. He also realized that the strength of compaction rocks increases with their degree of compaction, as indicated by water content, and they may tend to flow under load or removal of restraint. Cementation rocks on the other hand, are much more reliable and generally do not present strength problems.

CHAPTER IX

PRACTICAL APPLICATIONS

Petrographic Studies

Petrographic study of soils and soft rocks has been recognized in recent years as a valuable tool in soil mechanics research (Mitchell, 1956; Morgenstern and Tchalenko, 1967 a,b,c, among others). The primary advantage of petrographic studies is the possible detailed visual examination of the material under investigation; an example of which was provided by a thin section cut from a direct shear specimen of a fine-grained rock studied previously at the University of Alberta (Sinclair and Brooker, 1967). If this sample had been cut so that the failure plane was imposed one-eighth of an inch lower, the direct shear test results would not have fit the strength data from the test series and the researchers would have been hard pressed to explain the anomaly. However, the thin section revealed a petrified wood fragment about one-eighth of an inch from the actual failure plane! The following discussion will attempt to illustrate further the above concepts and in so doing, will elucidate the influence of minor geologic detail on the shear resistance of fine-grained rock.

Most studies, which attempt to relate effects of composition and texture on other soil properties such as shear resistance, are based on quantitative evaluation of bulk characteristics only, e.g. plasticity, grain size distribution. Thin section studies, on the other hand, may provide visual inspection of rock composition, its mode of occurence, and the morphology of this occurence. For example, if montmorillonite is present, is it disseminated or concentrated and if concentrated, what is the shape of the concentration?

Montmorillonite is of particular interest because of its "contribution" to the shear strength of the Alberta rocks hence its influence on slope instability in central Alberta (Sinclair and Brooker, 1967; Sinclair, Brooker and Thomson, 1966). Montmorillonite (bentonite) seams of variable lateral extent and thickness may be noted in both drillhole and outcrop. Petrographic study reveals that similar modes of occurrence occur on the microscopic scale (Plate 11, Figure 1; Plate 2, Figure 1; and Plate 2, Figure 2). The significance of the mode of occurrence of montmorillonite to shear resistance may be explained by the following hypothetical example. Two soft rocks may exist with equal concentrations of montmorillonite - say 5 per cent. If the montmorillonite is disseminated in one rock, then its effect on shear resistance is very small or negligible. However, if the other rock has a concentrated seam of montmorillonite (e.g. 5 per cent can provide a layer one millimetre thick in a twenty millimetre height), a definite zone of

weakness exists. X-ray analysis can provide an answer to the per cent montmorillonite present but cannot reveal the reason for the variation in the strength characteristics however, the explanation may be found in petrographic analysis. The application of this example to laboratory studies is readily apparent. In the field the presence of montmorillonite or bentonite micro-seams will contribute to slope instability in accordance with their frequency and location. A thin seam may, in fact, dictate the stability of an entire slope.

In some instances montmorillonite (bentonite) is present in the form of small lumps and imparts a brecciated structure to the rock (Plate 10, Figure 2). Whether or not such structures cause a greater peak resistance to shear than montmorillonite seams is not indicated by the test results. However, it is conceivable since such lumps may give rise to the development of a more irregular failure path than a seam. The residual strength of an undisturbed rock with a brecciated structure has been shown to be greater than the residual strength of a remoulded sample of the same material (Pennell, 1969). The remoulded sample exhibited a well-oriented texture with definite orientation of particles along the failure plane but the undisturbed sample exhibited negligible orientation along the failure plane with minor patchy orientation in the ambient material. Thus, with these materials, it does not appear feasible to determine representative values of residual strength parameters from remoulded specimens.

Brecciated structures also show a tendency to develop fissures along the outlines of the breccia (Plate 10, Figure 2) thus, in the field these fissures provide locations for a gradual softening of the mass due to ingress of water, with a resultant reduction of strength.

The influence of organic content on shear strength was not detected in the statistical analysis of this study. Nevertheless, the organic content may influence shear strength, since zones of weakness may occur either within organic matter or at contacts with adjacent materials. For example, during the preparation of direct shear specimens, samples often split readily along planes which contained substantial quantities of organic matter. It is suggested that weak correlation between organic matter and shear strength for the Alberta rocks results from the dominating influence of other compositional factors, e.g. clay content.

The influence of the morphology of the organic content on shear strength is suggested by a study of Plate 9, Figure 1 and Plate 11, Figure 2. Where organic fibers are parallel to the bedding, failure planes will be relatively straight and smooth thus, they may exhibit lower shear resistance than curved or irregular seams, which favour the development of irregularities. In any event, organic matter may influence the position of a failure path thus, in the field a failure zone through a highly organic, soft rock may contain numerous shear lenses, i.e. a brecciated zone.

The above discussion illustrates the significance of minor geologic detail on the shear resistance of fine-grained rock and shows that petrographic studies are desirable to assist in the evaluation of rock strength. The significance of minor geologic detail on engineering works and structures was emphasized by Terzaghi on at least two different occasions (Terzaghi, 1929 and 1962).

In 1929 he stated:

> "Minor geologic details" refer to features that can be predicted neither from the results of careful investigations of a dam site nor by means of a reasonable amount of test borings. They include such items as the exact position and the variations in width of fissures passing through the rock beneath a dam foundation, the shape and local variations of the permeability of minor seams of coarse sand and gravel contained in fine-grained alluvial valley fills, and similar features of minor geologic importance."

Later in 1962 he stated:

> "All foundation failures that have occurred in spite of competent subsurface exploration and strict adherence to the specifications during construction have one feature in common. The seat of the failure was located in the weak layers or in "weak spots" within very limited dimension."

Terzaghi (1962) points out that the weak spots must be located, the properties of these weak zones determined, and the results incorporated into the design, because geologic conditions do not exclude weak zones therefore they cannot be neglected.

Geologic Application

In view of the fact that neither petrographic studies nor any other form of systematic study has been performed previously on the near surface, fine-grained rocks of central Alberta, the descriptions of the geotechnical characteristics of these materials may be of interest to the geologist as well as the engineer. Based on the findings of this report, there appear to be three major aspects which may appeal to geologists for future research; these are:

(1) the contribution that a detailed study of the systematic variation in bulk density may make to unravelling the geologic stress history of the area.

(2) the significance of the apparent change at the Entwistle area from compacted rocks to the east to cemented rocks to the west.

(3) verification, through detailed studies, of the proposed effects of diagenesis on the characteristics of the fine-grained rocks.

This report presents sufficient data only to suggest that a systematic variation in bulk density of the Alberta rocks does exist. Further, more detailed studies should include additional horizontal control and a study of the rocks to depths of a thousand feet or more to provide vertical control. Detailed, systematic studies of bulk density over a wide area and great depths may provide information on relative compressive

stress and thus, assist to unscramble the stress history of the rocks of central Alberta.

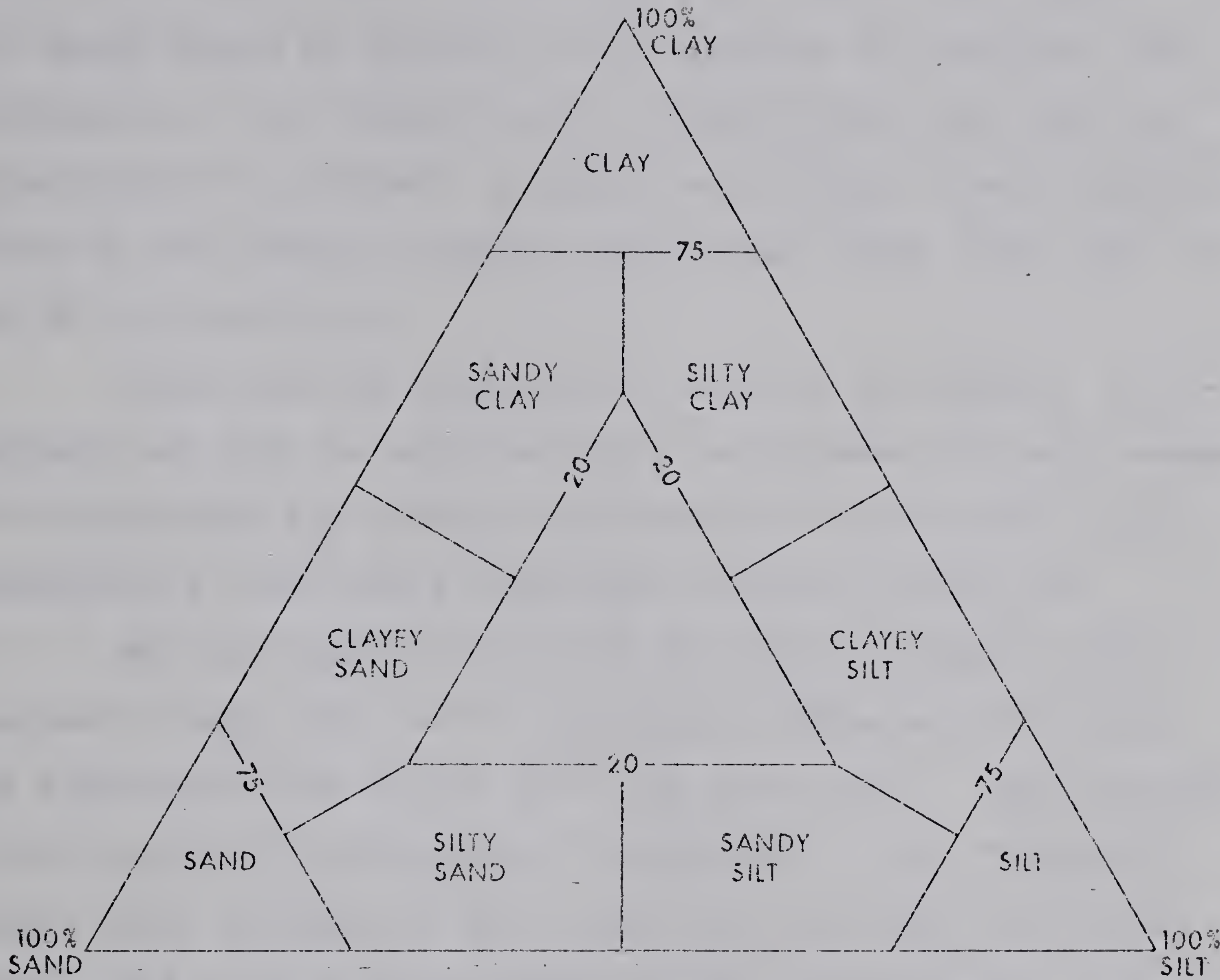
The apparent change from the compacted rocks of the eastern portion of the study area to the cemented rocks of the western portion at Entwistle roughly coincides with the location of the Upper Cretaceous-Tertiary contact, as proposed by Rutherford (1928). It is appreciated that the associated data is extremely limited however, the above analogy may assist future correlation studies, particularly in view of the fact that criteria for distinguishing the Tertiary from Upper Cretaceous rocks are weak.

Classification of Fine-Grained Rocks

A classification system is composed of groups with appropriate nomenclature into which may be placed materials of a specific description. Effective communication between individuals requires such a system, which to be successful, must have the general agreement of all who require it. Unfortunately, because of the extremely wide range and variability of the characteristics of sedimentary rocks, no mutually acceptable classification system exists for these materials. Pettijohn (1957) discuss this problem and suggests that partial classification systems be employed, i.e. classification systems for related groups of materials such as clastic sediments. The definitions employed in this report for fine-grained rock and soft rock types were presented in Chapter II (Definition of Terms). The troublesome feature in these definitions lies

with the recognition of fissility; to be classed as a clay-shale or shale, the material must be readily fissile (Pettijohn, 1957; Williams et al, 1954; Spock, 1953; Krumbein and Sloss, 1963). Many researchers, particularly in the field of soil mechanics, do not observe the above criteria, hence many so called "shales" or "clay-shales" in the literature are actually claystones or even siltstones. The danger of such inconsistencies in usage of terminology is that engineers in localized areas each have their own "shale" or "clay-shale" and comparisons with materials outside these local areas may be misleading. The classification of a material as a shale should be decided from the unweathered material because weathering of a claystone or siltstone can develop an apparent "fissile" structure. The term clay-shale has found wide usage, particularly in Western Canada. The author advocates that this term should be restricted to fine-grained, soft rocks which are readily fissile and upon rebound and weathering revert to soils which behave similar to highly overconsolidated clays. In any case, indiscriminate use of the terms shale and clay-shale should be guarded against and the terms siltstone and claystone should be applied in their correct connotation.

The fine-grained rocks of central Alberta are mainly siltstones and claystones, with those from Cadomin classed as shales. In order to place the correct nomenclature on the rocks, the Shepard textural chart (Figure 28) was used because it enjoys common usage by geologists, to whom the study of



TERNARY DIAGRAM FOR CLASSIFICATION OF ROCKS

(after Shepard)

FIGURE 28

sedimentary rocks belong in the first instance. With this chart a descriptive name may be applied to the rock, e.g. sandy siltstone, silty claystone, etc. Since this system is based solely on particle sizes and does not consider the influence of clay mineral type, a descriptive term based on plasticity is included. Materials with liquid limits greater than 50 are classed as highly plastic and those lower than 50 as of low plasticity.

Terms such as compacted or cemented and organic or inorganic may also be employed but in most cases the name becomes too cumbersome for average use therefore they may be used as descriptive terms along with color, geologic name, etc.

The descriptive names for the Alberta rocks are presented in Table III but the plasticity characteristics must be determined from column 16 of the same table. Those Alberta rocks which were recognized as bentonites in the field were named such, although in accordance with the above procedures they could be classed as highly plastic siltstones or claystones.

Shear Strength and Slope Stability

Interest in the shear resistance of the rocks of central Alberta was mainly confined until recently to the Edmonton area where there is a concentration of engineering works and coincidently less competent rocks, as illustrated by numerous cases of instability along the North Saskatchewan

River. Recently, however, the interest in water control structures has risen and future dam sites are under consideration between Edmonton and the Foothills. In projects of this nature long term shear resistance must be considered and in the light of recent research by Skempton (1964) and Bjerrum (1967) and the risk factor involved in such projects, design considerations must take residual strength concepts into account.

In this report, different parameters of residual strength are reported for undisturbed samples, remoulded samples, and samples with precut failure planes, of which the results from undisturbed samples are considered herein to be most representative of shear conditions in the field. The higher residual strength associated with undisturbed samples is suggested to be a direct manifestation of the irregularities on the failure surface. Studies of actual slip surfaces in the field show that irregularities and shear zones which contain numerous shear planes and shear lenses do exist in a variety of material types. For example, Morgenstern and Tchalenko (1967a) noted the above phenomena in a varved silt (Cod Beck), silty clay (Fiddlers Ferry), London clay (Guildford), Oxford clay (heavily overconsolidated, fissured clay, Peterborough) and Atherfield clay (soft clay, Sevenoaks). Skempton (1966) presented an extensive discussion of tectonic shear zones in a compact clay at the Mangla Dam project and in a hard siltstone at Lough Fee in Ireland. Thus, despite the lack of research on actual failure zones in the central Alberta rocks, it appears reason-

able in the light of observations of the above workers and this research to assume that failure surfaces of a comparable nature may develop in the Alberta rocks and that the residual strengths of undisturbed samples are representative of natural shear conditions. However, whether the residual cohesion intercept is applicable in the field or not is open to question. The above discussion which substantiates the use of undisturbed samples may also be directly applied to justify the existance of residual cohesion, if as has been suggested, the cohesion is a manifestation of an irregular failure surface. However, as previously discussed, the cohesion intercept is susceptible to considerable variation inherent in the determination of the best fit rupture line from scattered data. The design engineer, therefore may be reluctant to employ the best fit cohesion intercept in design but may desire to select the lowest value of cohesion intercept, as exhibited by an individual sample of a series. Actual slope stability problems are not an integral part of this project therefore the above suggestions cannot be tested. However, it may be noted that Pennell (1969) found that cohesion must be considered to exist along the failure plane, in order to arrive at a factor of safety of unity with the application of residual strength concepts for slopes in the Edmonton area. Testing programs to evaluate the potential residual strength parameters should consider normal loads representative of field conditions because, as previously suggested, the rupture line may curve at higher normal loads

where more projections fail.

The shear strength characteristics of the Alberta rocks are shown to increase generally in an east-to-west direction (Table XII) in keeping with field observations for the propensity for slope instability. The steep river valleys of the Edson area and west are a reflection of the high peak strengths determined in this study; river bank slopes and the effective peak angles of shear resistance are of comparable magnitude. In general it may be stated that the rocks of this area are competent but if a slope fails as a result of severe undercutting by river erosion, the movements are apt to be rapid perhaps with no warning of failure, i.e. similar to a rock fall. This latter fact is suggested by the large drop in shear resistance after the loss of peak strength as illustrated by the strength ratios.

In the Entwistle area, the rocks exhibit peak strengths comparable to steep "stable" slopes of the river banks near corehole and outcrop sites, however there is evidence of some slope instability in this region (S.R. Sinclair pers. comm.) As previously suggested, the Entwistle region appears to be the area in which the rocks are changing from basically compacted materials to those of a cemented nature therefore some instability may be expected in this area, particularly within the compacted rocks.

In the rocks of the Entwistle area and west, it is suggested that detailed studies of bond strength (wet-dry cycle

tests) and of the degree of fissuring on both the macroscopic and microscopic scale are quite significant to the evaluation of the competence of the rocks. Wet-dry cycle tests will reveal the susceptibility of the materials to weathering and the nature of the rocks, i.e. compacted or cemented. The degree of fissuring, among other factors, will reveal the reliability of the peak cohesion intercepts as determined in the laboratory. For example, the variation of the peak cohesion for the P-54 series (relatively constant angle of shear resistance) may be attributed to the presence of micro-fissures in the rock.

The effective residual angles of shear resistance, ϕ_R' of the rocks of the Entwistle area and west are in the neighborhood of 20 to 32 degrees with the exception of P-54 which is at the border of cemented and compacted materials (wet-dry cycle rating = 11). With such high values of ϕ_R', very conservative designs of reservoir slopes, etc., can be made on the basis of residual strength but retain relatively steep slopes.

The compacted rocks of the Edmonton area are believed to lose strength with time and ultimately fail at a strength value close to or at residual strength (Sinclair, Brooker, and Thomson, 1966; Pennell, 1969). These rocks are believed to have bonds which are generally of a viscous nature and are very susceptible to weathering, hence a gradual loss of strength results in long term movements of a slope to some attitude comparable to the effective residual angle of shearing resistance, e.g. Grierson Hill, (Pennell, 1969).

CHAPTER X

CONCLUSIONS

Much of the material presented in the report is of a descriptive nature consequently the conclusions presented are, in many instances, only a very brief general summary of the pertinent facts. It appears that the following conclusions are justified in the light of the test results on <u>selected samples of the near-surface, fine-grained rocks of central Alberta.</u>

1. The Alberta rocks are predominately siltstones with minor occurrences of claystones and bentonites. In general the rocks progress from compacted rocks in the eastern portion of the study area to cemented rocks of increasing induration as the Foothills are approached. The rocks represent a transition zone from true "soils" to true "rocks" (grey zone).

2. In a general manner the composition of the Alberta rocks may be summarized as follows (components arranged in order of relative occurrence):

(a) sand-plus silt-size fraction: quartz and feldspar, mica, volcanic rock fragments, and carbonate fragments;

(b) clay-size fraction:	montmorillonite, illite, chlorite, and kaolinite;
(c) cements;	carbonates, iron oxides, and silica;
(d) salts:	calcium, magnesium, sodium, and potassium
(e) miscellaneous components:	organic (coal-like) matter, and pyrites.

3. The major textural features of the Alberta rocks are:

(a) selective sorting action of the rivers which carried the detritus from the source area resulted in a higher percentage of clay-sized fraction in the eastern portion of the study area; only the Edmonton Formation materials have a percentage of clay greater than 40 per cent. In general, the majority of the rocks contain large proportions of silt-sized material.

(b) the coarser fractions of the rocks generally are angular in shape.

(c) preferred orientation of the grains (sand-, silt- or clay-sized) is a minor feature of the fine-grained rocks. Concentrated pockets of montmorillonite however, are often well-oriented.

The major textural patterns noted in the rocks are:

(a) predominately sand-and silt-sized material in a small percentage of clay matrix.

(b) the above textures (a) grade with decreasing percentages of coarser-grained constituents to predominately

fine-grained clays with a few floating silt grains.

(c) shard textures are found in most highly bentonitic rocks reflecting their volcanic origins.

4. Structures in the Alberta rocks are summarized as follows:

(a) primary structures

Laminations caused by alternations of (a) coarse and fine-grained particles, (b) alternations of material of different composition, e.g. quartz and organic debris, calcium carbonate and quartz silt. Pellets and brecciated structures also impart primary structure to the rock.

(b) secondary structures.

Secondary structures which develop in early stages of diagenesis in the rocks are slump features, and ironstone nodules. Secondary structures which develop during later stages of diagenesis are fissility and various other types of physical discontinuities such as fissures.

5. The plasticity characteristics of the Alberta rocks vary widely, with the most plastic material being bentonite. The most efficient predictor of the variation in plasticity is montmorillonite, as illustrated by multiple regression analyses. The closely correlated variables clay content and sodium ion content are minor contributors to the variation in plasticity.

6. The bulk density of the rocks increases systematically in an east-to-west direction across the study basin. This increase in bulk density appears to be attributable to an increase in past overburden pressures and in horizontal compressive forces (associated with mountain building) as the Foothills are approached. Montmorillonite is shown by multiple regression analyses to be the most significant compositional "contributor" to the variation in bulk density with clay content and carbonates as minor factors.

A decrease in bulk density of outcrop samples as compared to corehole samples decreases as the Foothills are approached because of an increase of the resistance of the soft rocks to weathering.

7. The wet-dry cycle test is recommended as a technique for evaluating and distinguishing between rock types. For the Alberta rocks the wet-dry cycles indicate that the resistance to breakdown (weathering) increases in an east-to-west direction across the selected basin. The wet-dry cycle test appears as a simple means of evaluating the bond strength, the resistance to weathering of soft rocks, and distinguishing cemented rocks from compacted rocks. The wet-dry cycle tests also indicate in a relative manner the energy stored in the rocks.

Multiple regression analyses illustrate that bulk density and carbonate content are the most efficient "predictors" of

wet-dry cycle rating.

8. In a general way, the effective shear strength parameters increase in magnitude in an east-to-west direction across the study basin. Multiple regression analyses indicate the major "causal" factors of "strength" to be:

Strength Parameter	"Causal Factor"
ϕ_p'	Clay content
C_p'	Density, distance
ϕ_R'	Clay content
C_R'	Density, clay content

The development of "strength" in the Alberta rocks is explained in terms of bond strength and irregularities on the failure surface. The magnitude of strength loss after peak strength is exceeded appears to depend on bond type.

It does not appear feasible to attempt to evaluate the residual strength of the Alberta rocks from tests on remoulded samples.

9. Petrographic analyses are a valuable tool to assess the characteristics of fine-grained rocks and to discover the significant minor geologic detail in rocks that normally escape detection in typical engineering studies.

10. Diagenesis is suggested to be a major contributing factor to the development of the geotechnical characteristics of a fine-grained rock.

CHAPTER XI

RECOMMENDATIONS

Recommendations With Respect to Future Study Programs

1. The present design of the Pitcher sampler limits its use to compacted rocks such as those found in the Edmonton area. A core-barrel or a similar rugged drilling tool is required to obtain samples in the cemented rocks.

2. Petrographic analyses and wet-dry cycle tests should be included in all investigations on fine-grained, sedimentary rocks to aid in classification and in the evaluation of the bulk properties of the rocks. Where possible thin sections from the failure zones of rocks subjected to shear should be studied.

Recommendations for Future Research

1. A minor research project should be undertaken to thoroughly evaluate various systems to break fine-grained rocks down into "primary particles". Suggested breakdown methods are:

(a) for compacted rocks:
- wet-dry cycles
- freeze-thaw cycles
- grinder

(b) for cemented rocks -freeze-thaw cycles
-grinder

Freezing rates may be varied, hence evaluated, by utilizing dry ice, normal refrigeration equipment, and equipment available for the freeze-thaw testing of concrete. To evaluate the grain size distributions obtained, the results may be compared to detailed statistical point counts of actual grain sizes as viewed in thin sections. It is recommended that a relatively homogeneous siltstone be used to facilitate microscopic study. Thin sections should be cut immediately adjacent to samples subjected to grain size distribution.

2. The apparent systematic variation in bulk density should be thoroughly investigated with the intent of obtaining a further appreciation of stress history.

3. The shear strength testing program suggests that the evaluation of residual strength parameters from undisturbed samples requires further study at both higher and lower normal loads than employed herein. Such an investigation could evaluate the effectiveness of the contribution of irregularities to shear resistance and determine whether or not; (a) the residual rupture line does curve at higher normal loads, (b) a cohesion intercept exists at zero normal load.

4. To further evaluate the influence of diagenesis on the near-surface, sedimentary rocks of Alberta and the problems of slope instability it is recommended that a study comparable to this investigation be performed; (a) on the sandstones, (b) on both sandstones and finer-grained rocks across Alberta but to the north and south of the study area chosen for this investigation.

PLATE I

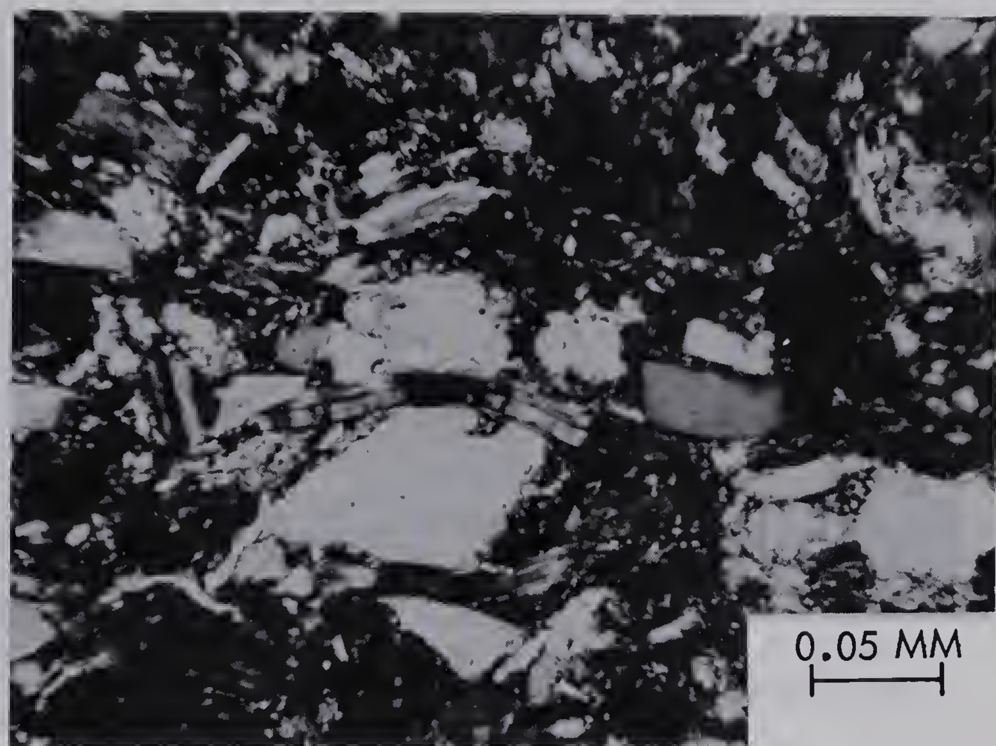


FIGURE 1. Coarse-grained, distorted, mica plate, [centre]. Sample MRR-9, crossed nicols.

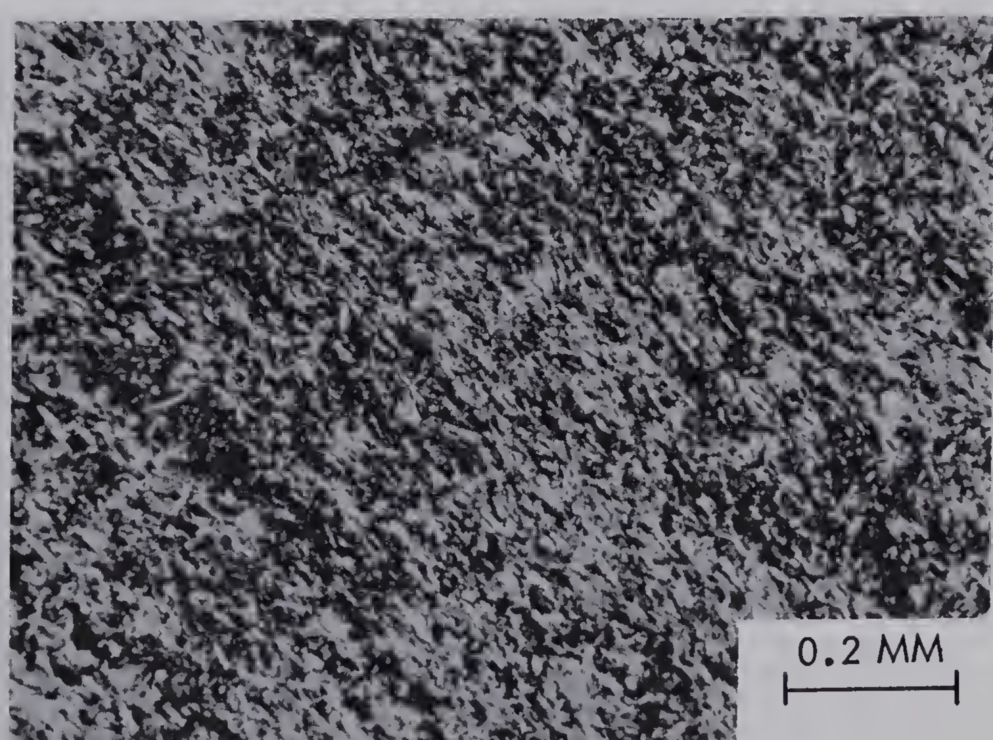


FIGURE 2. Fine-grained mica plates, [elongated white shreds]. Sample M-1, crossed nicols.

PLATE 2

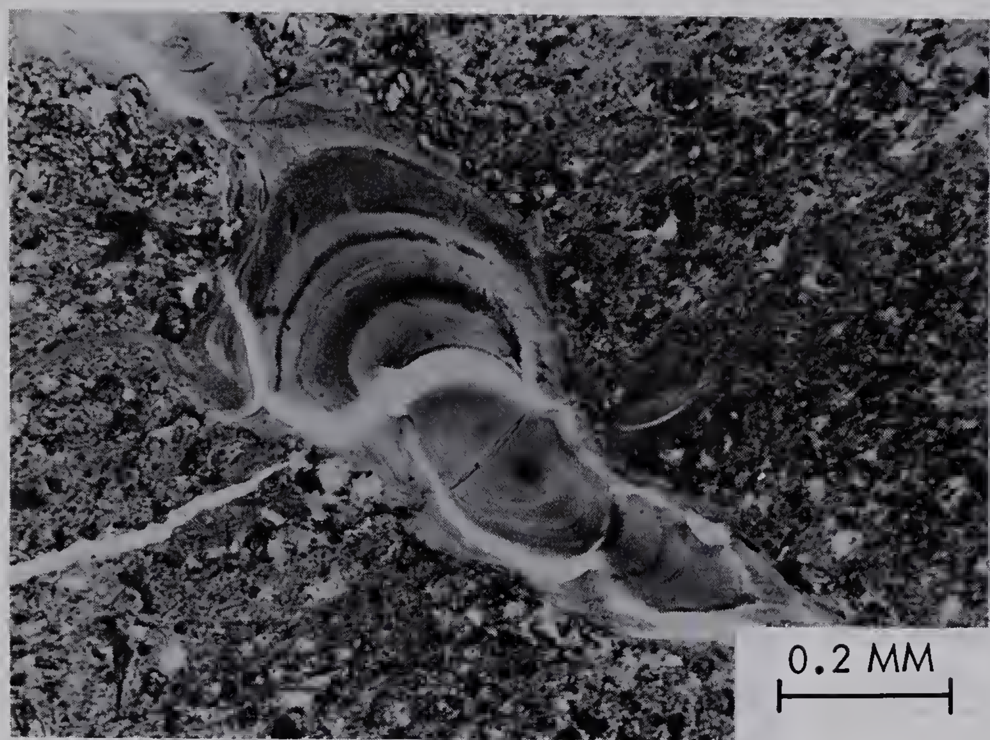


FIGURE I. Concentrated montmorillonite, originally a colloidal gel. Sample w-7, plane polarized light.

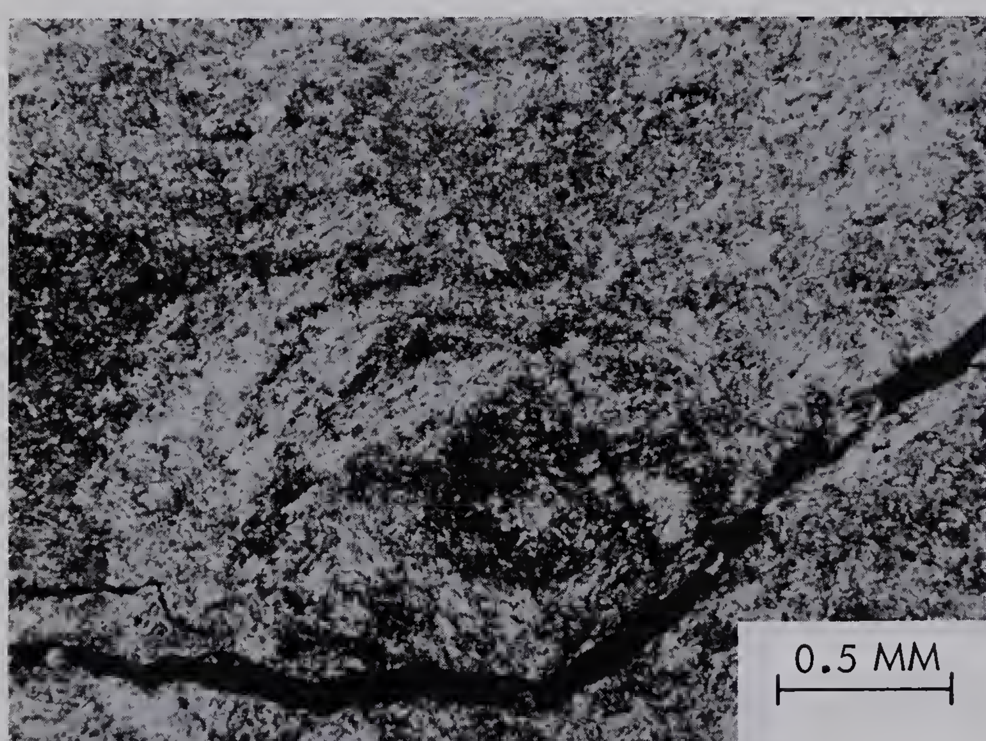


FIGURE 2. Montmorillonite, [light coloured material], "swirly" structure. Sample p-6, crossed nicols.

PLATE 3

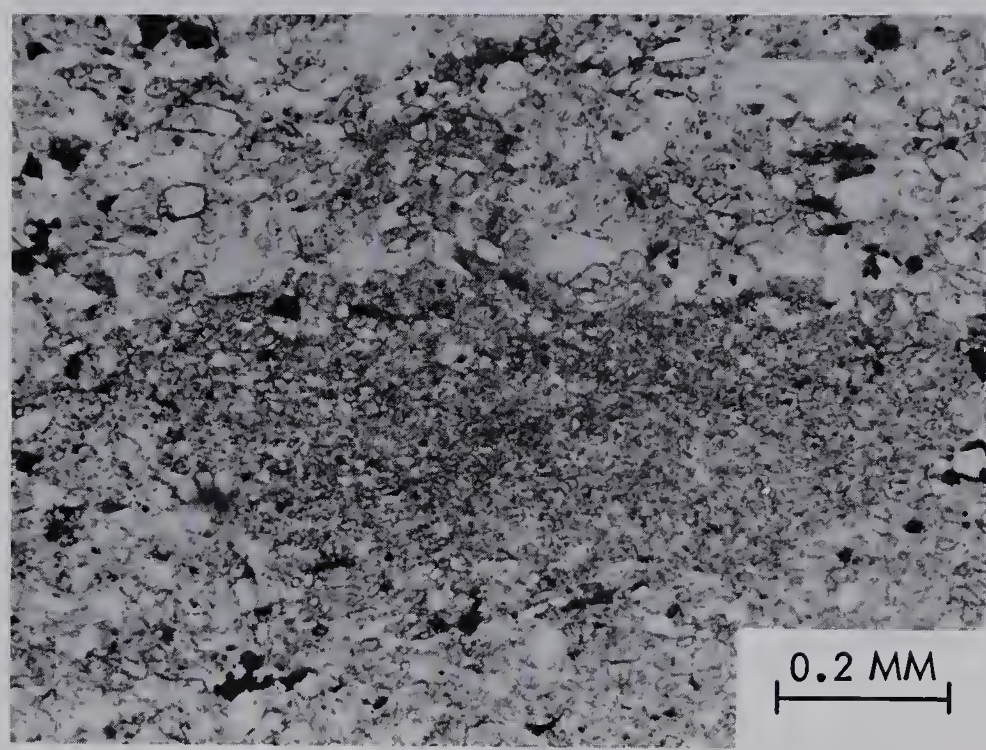


FIGURE 1. Patch of carbonate cement, [centre, dark patch]. Sample w-2, plane polarized light.

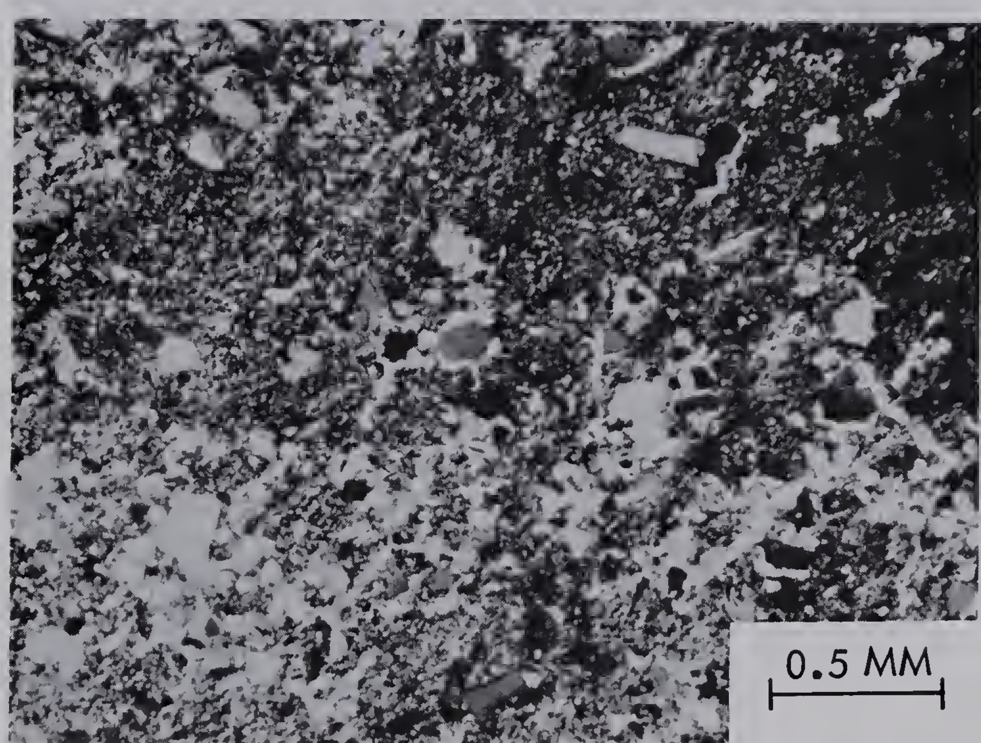


FIGURE 2. Carbonate cement in dendritic-like pattern, [white, elongated, irregular shapes]. Sample mc-1, crossed nicols.

PLATE 4

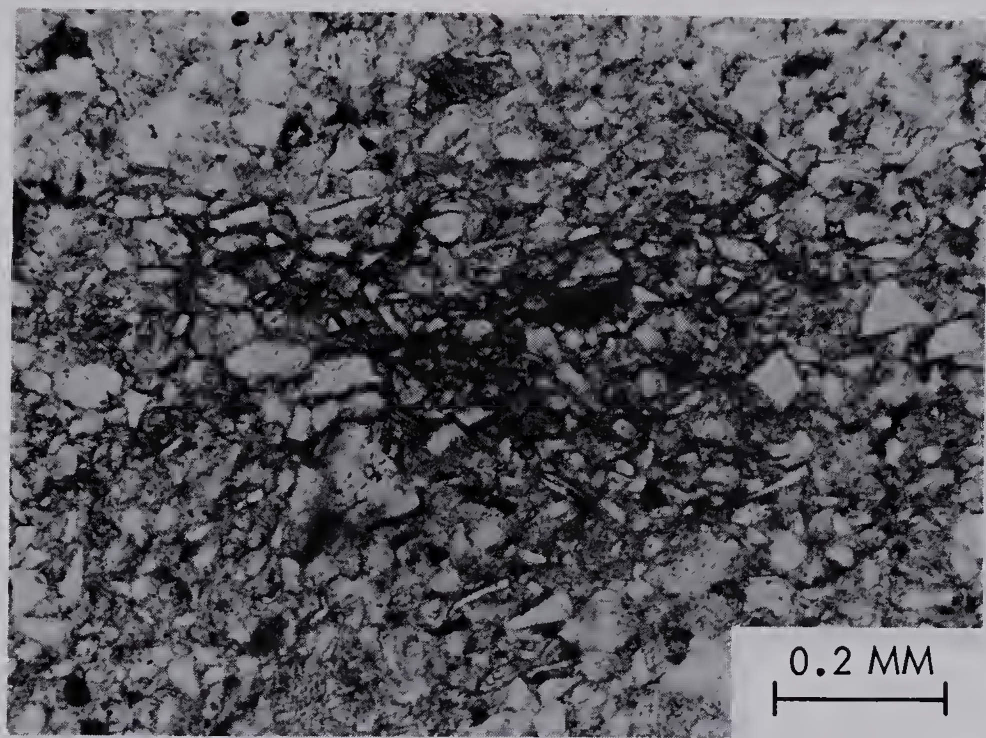


FIGURE I. Coarse-grained silty texture. Dark staining is organic matter. Sample mrr-4, crossed nicols.

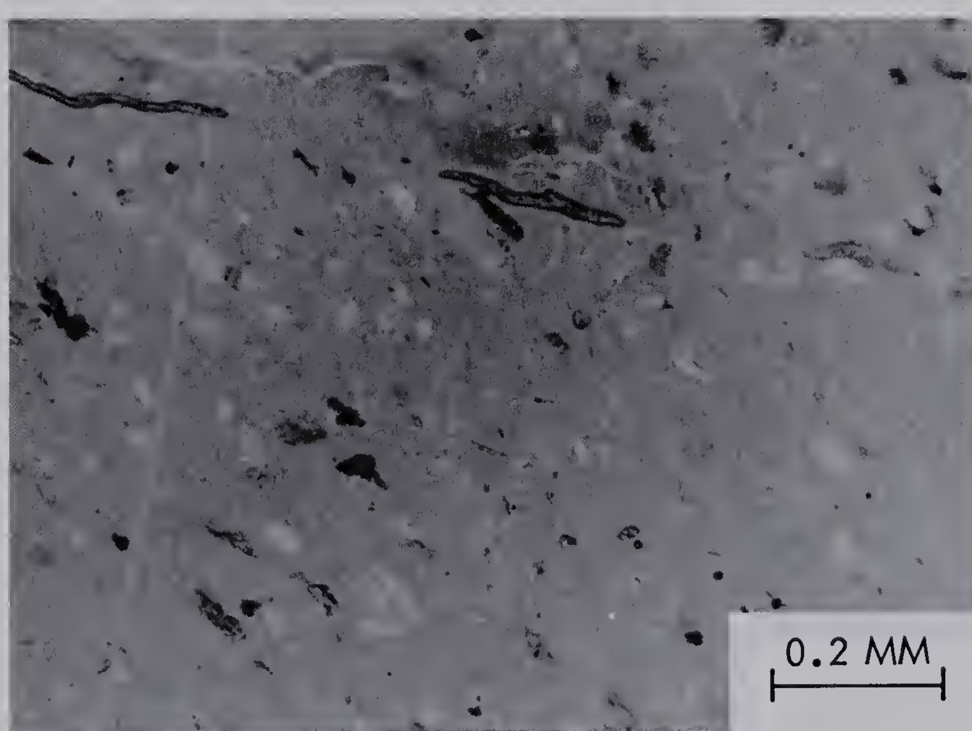


FIGURE 2. Bentonitic siltstone with very low silt content. Sample rb-i, plane polarized light.

PLATE 5

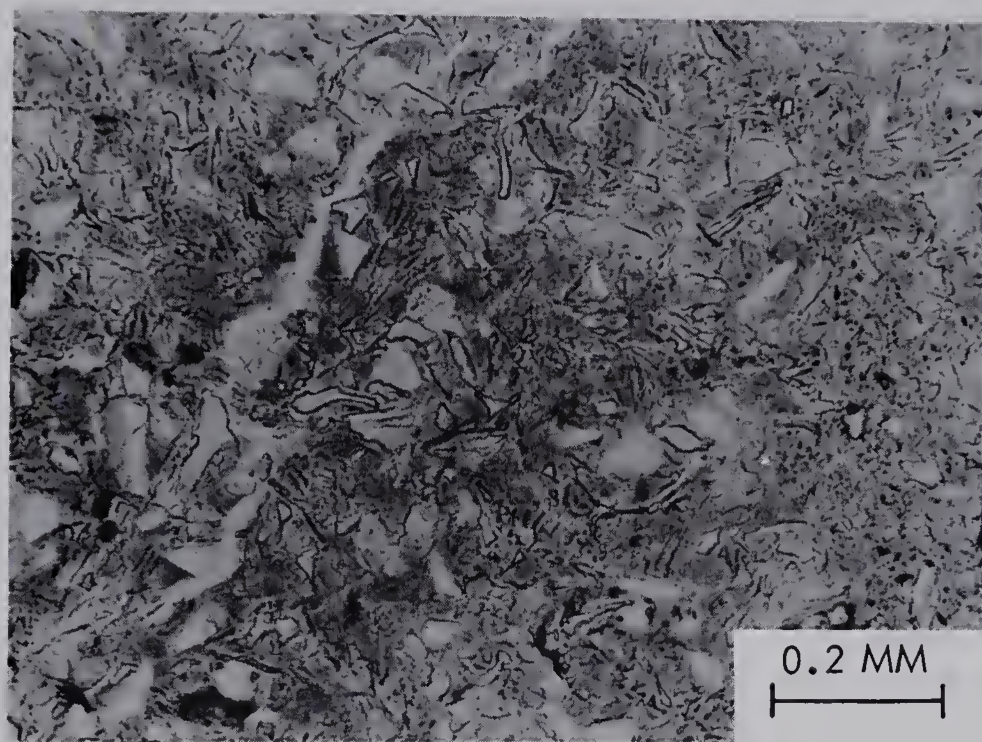


FIGURE 1. SHARD TEXTURE. SAMPLE MRM-2, PLANE POLARIZED LIGHT.

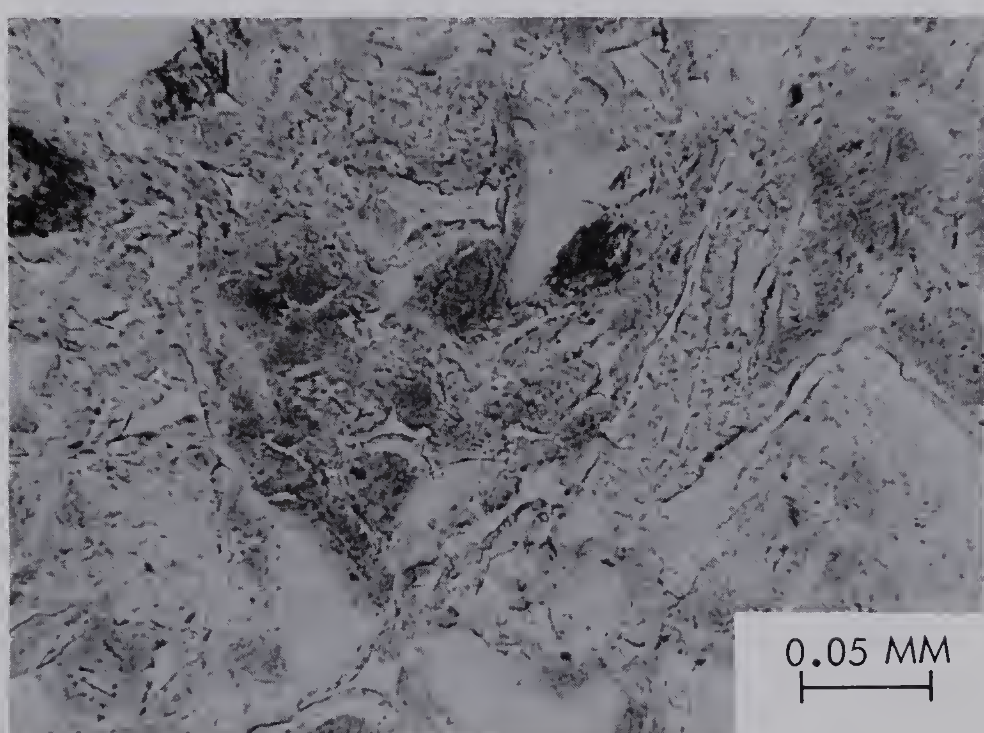
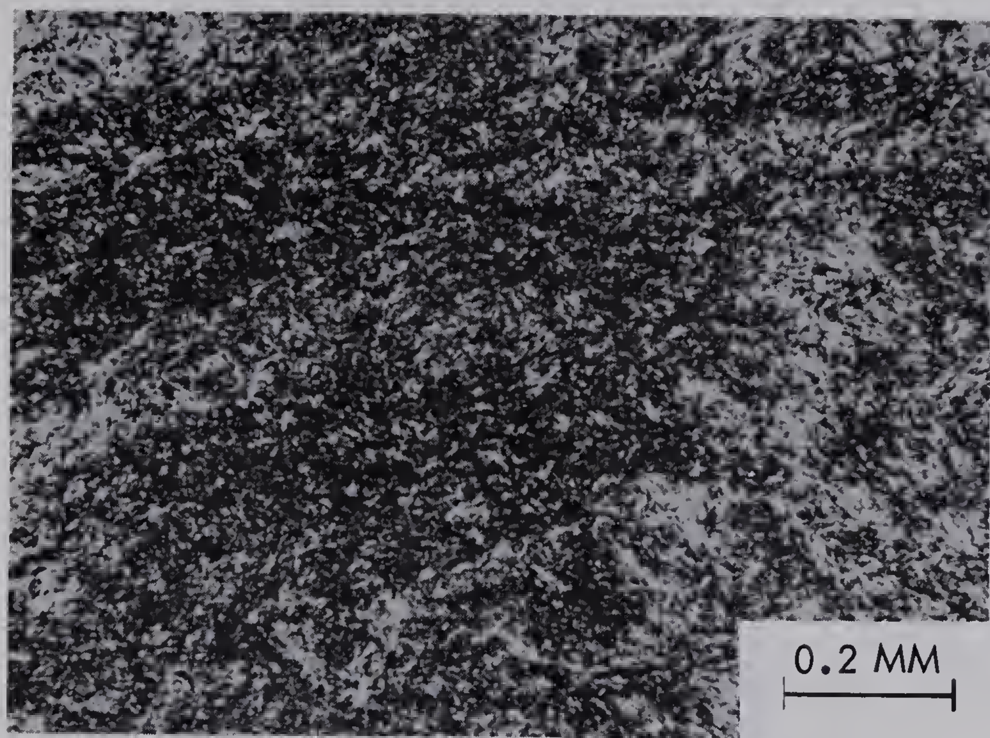


FIGURE 2. SHARDS, SPICULE-LIKE FORMS. SAMPLE MRM-2, PLANE POLARIZED LIGHT.

PLATE 6



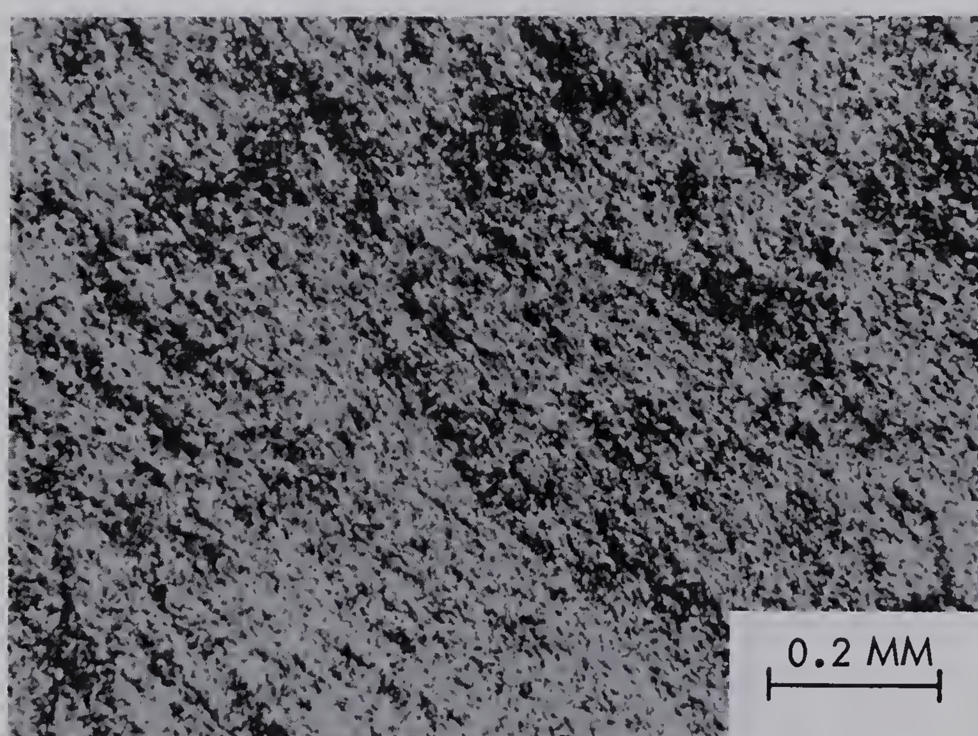
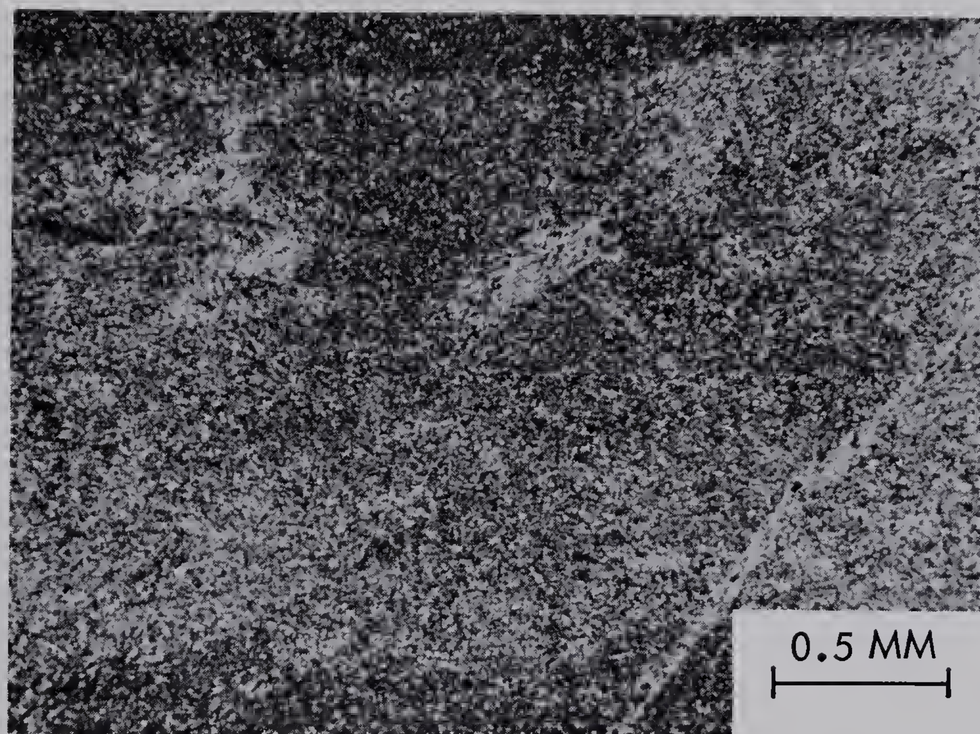


FIGURE 1, 2. ORIENTED CLAY AGGREGATES. UPPER PICTURE AT 0°, LOWER PICTURE AT 45°. SAMPLE P-6, CROSSED NICOLS.

PLATE 7



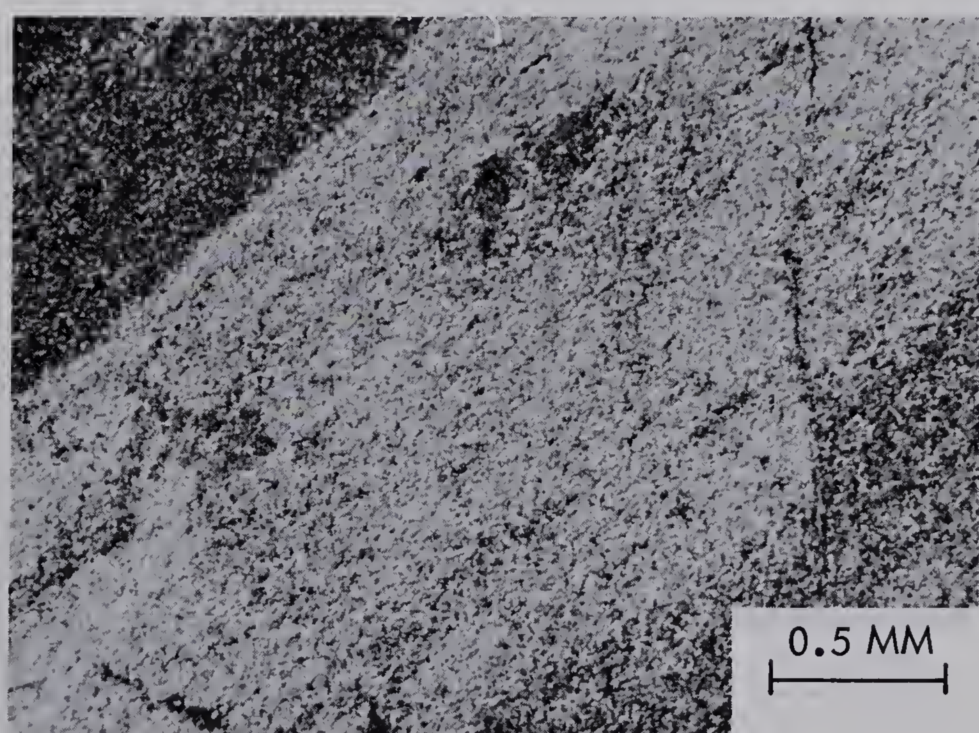


FIGURE 1, 2. Band of oriented clay aggregates.
Upper picture at 0°, lower picture at 45°.
Sample p-33, crossed nicols.

PLATE 8

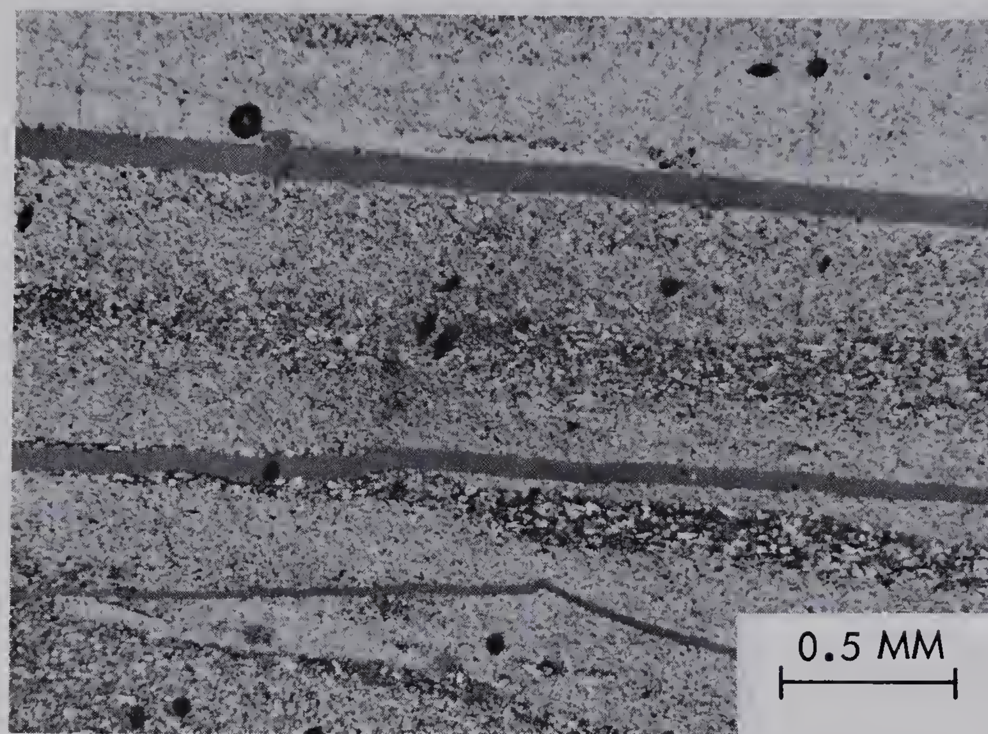


FIGURE 1. Laminated structure caused by grain size variation. Sample M-4, crossed nicols.

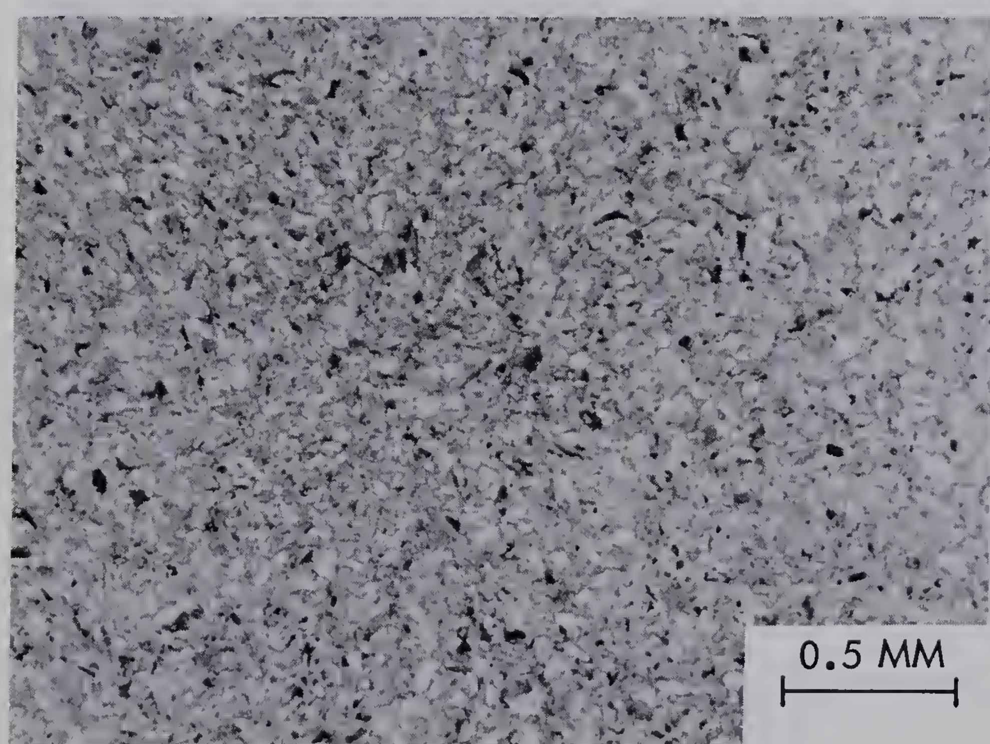


FIGURE 2. Homogeneous structure. Coarse silt in clay matrix. Sample MRR-4, plane polarized light.

PLATE 9

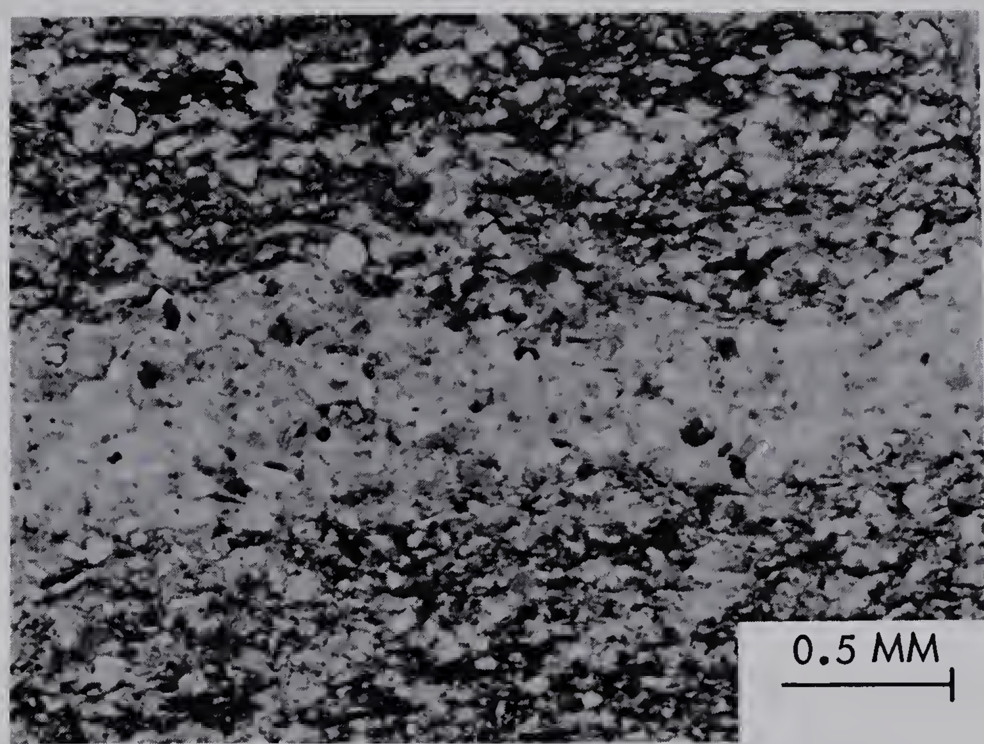


FIGURE I. Laminated structure accentuated by organic matter. Sample AGT-2, plane polarized light.

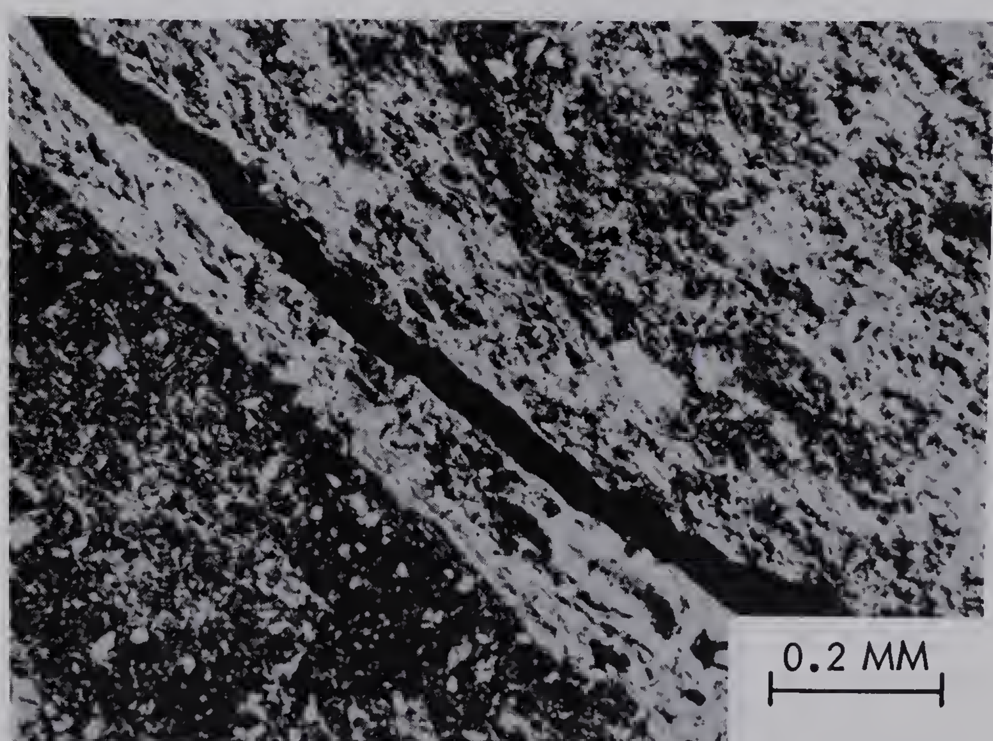


FIGURE 2. Crack controlled by montmorillonite, [light coloured material], Sample W-7, crossed nicols.

PLATE 10

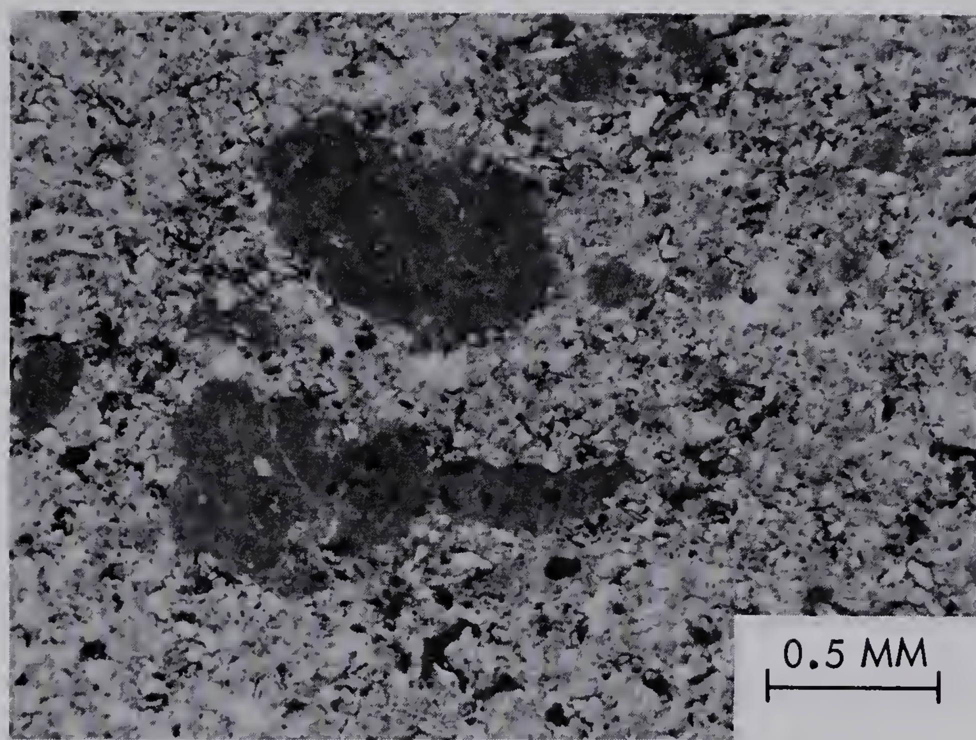


FIGURE 1. Pelleted structure, dark inclusions are clay pellets. Sample W-1, plane polarized light.

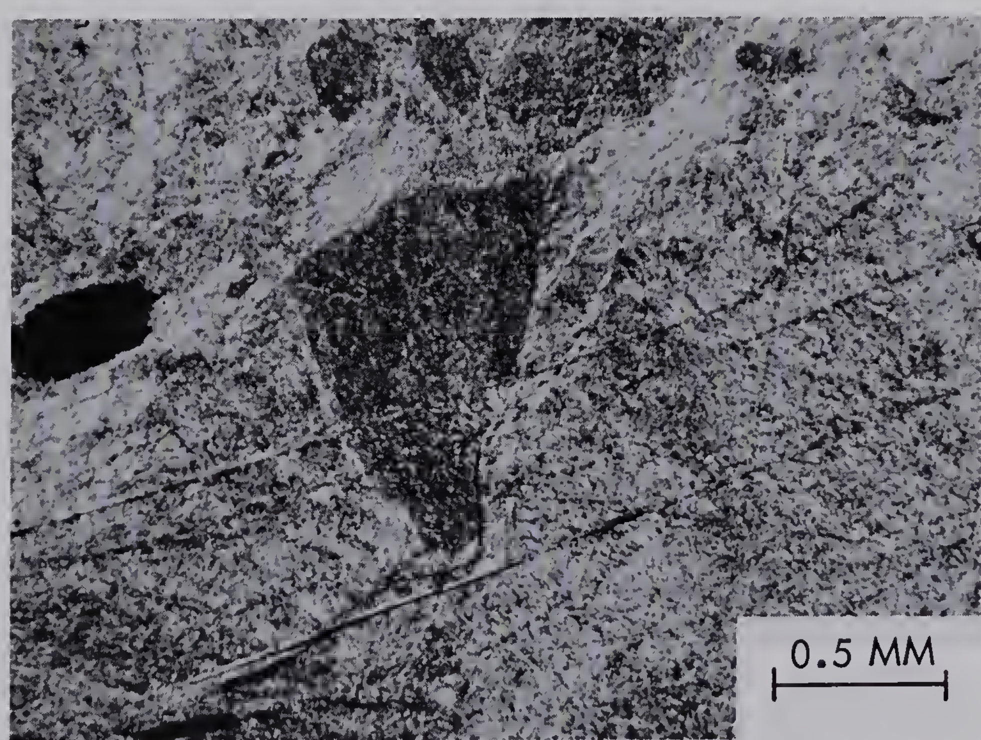


FIGURE 2. Brecciated structure in bentonitic claystone. Sample RB-2, crossed nicols.

PLATE II

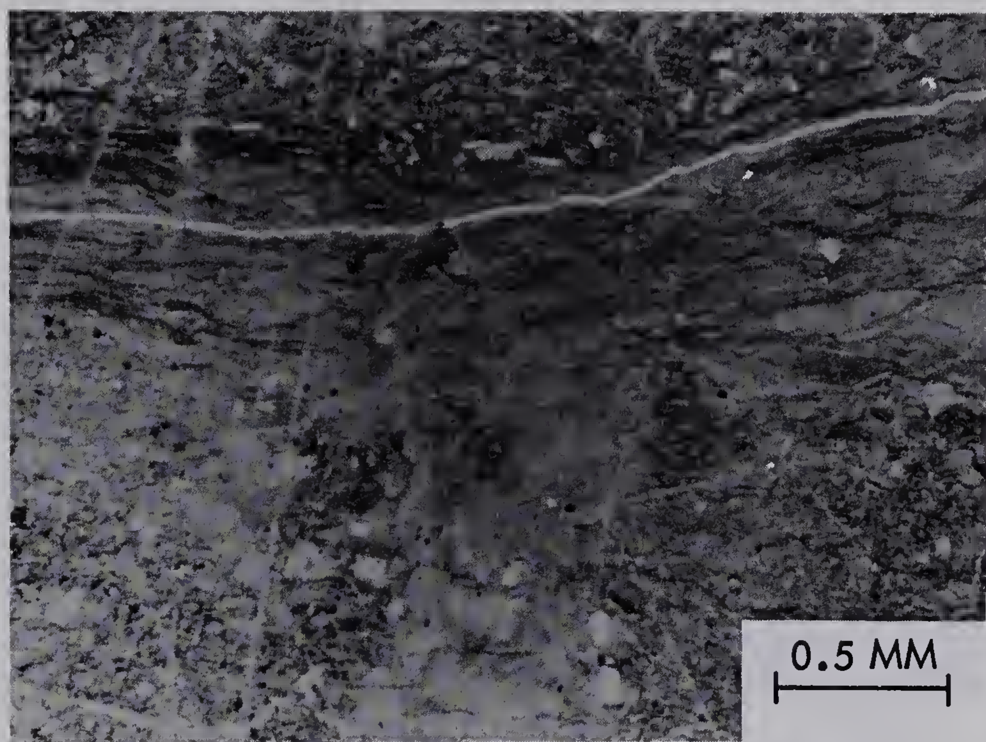


FIGURE 1. Structure, montmorillonite infilling. Sample w-6, plane polarized light.

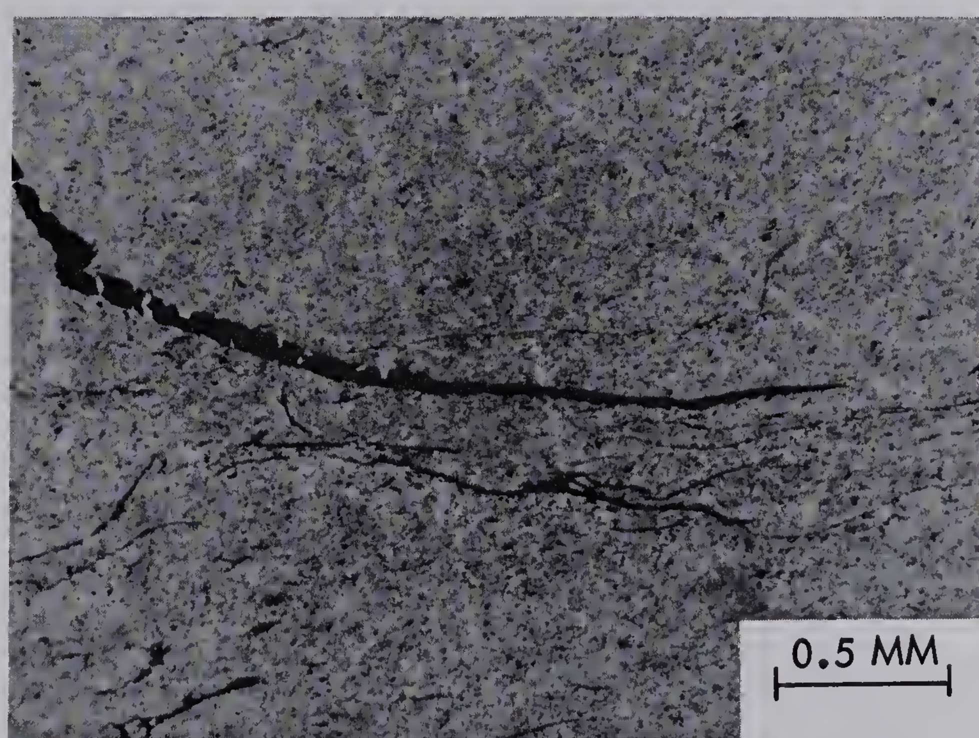


FIGURE 2. Structure, organic matter parallel and subparallel to bedding. Sample w-8, plane polarized light.

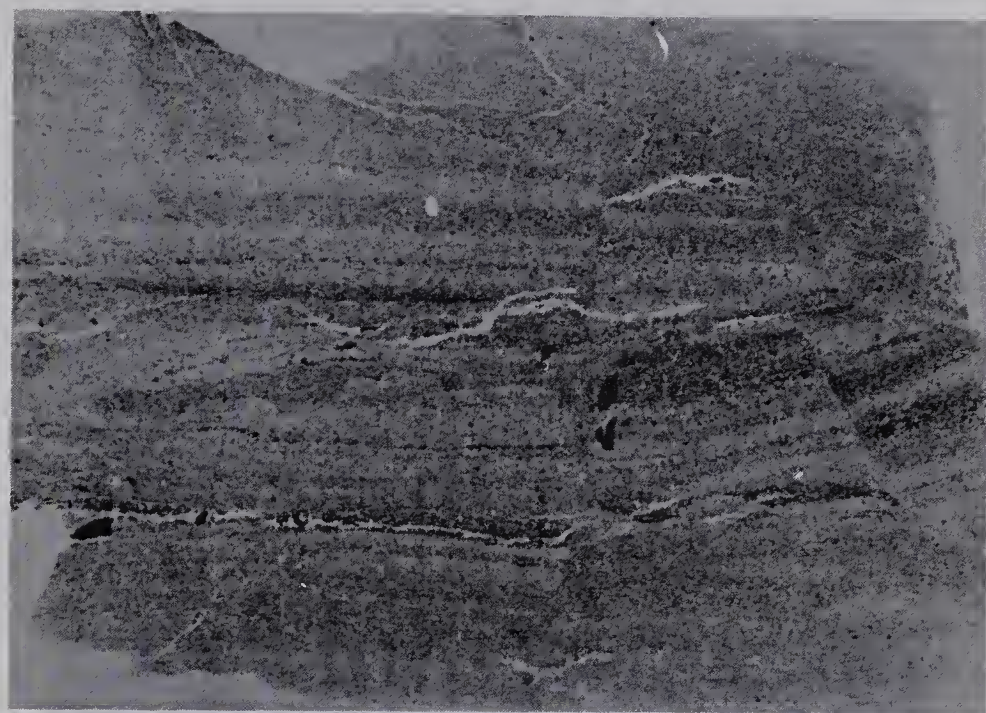


FIGURE 1. Photograph of entire thin section to show slumped structure. Sample AGT-2, enlarged approximately four times.

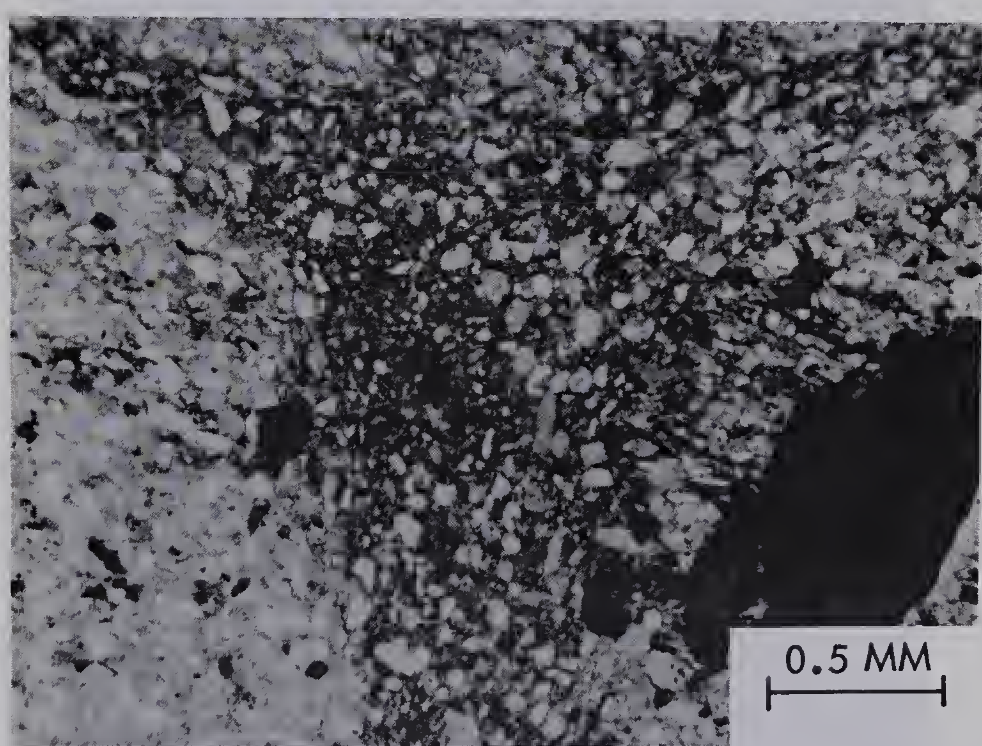


FIGURE 2. Photomicrograph from above thin section to show infilling, [locate by pyrite growth]. Sample AGT-2, plane polarized light.

PLATE 13

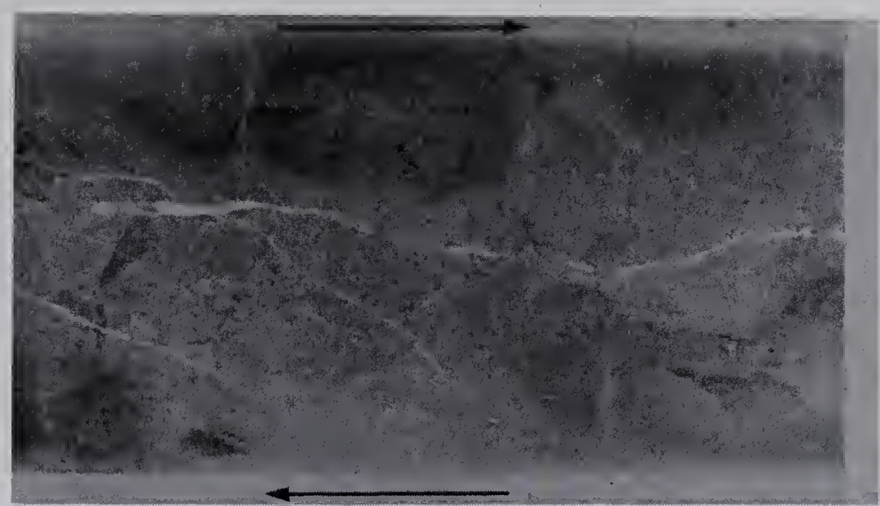


FIGURE 1. Type I cracking pattern
Sample mrr-74d

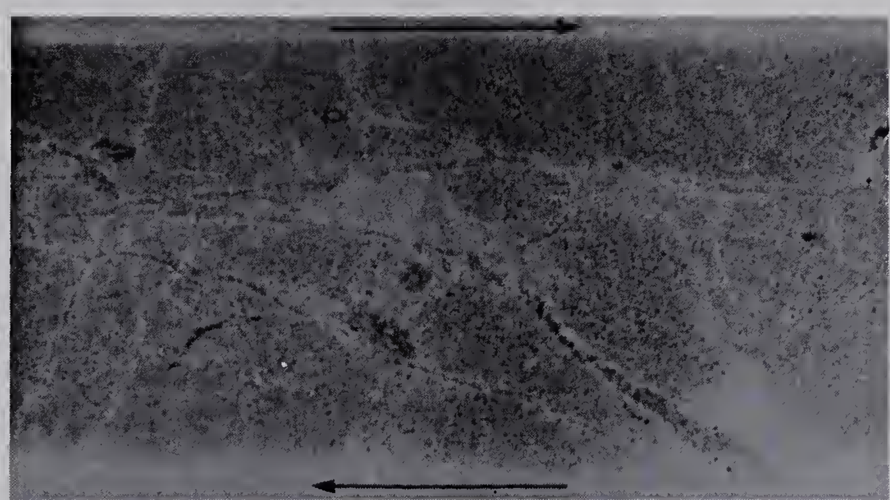


FIGURE 2. Type I cracking pattern
Sample mrr-45g

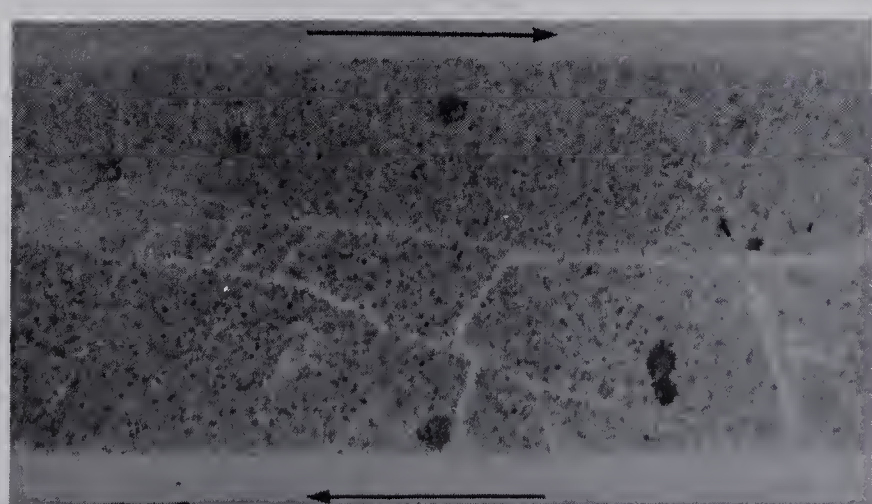


FIGURE 3. Type I cracking pattern
Sample mrr-45f

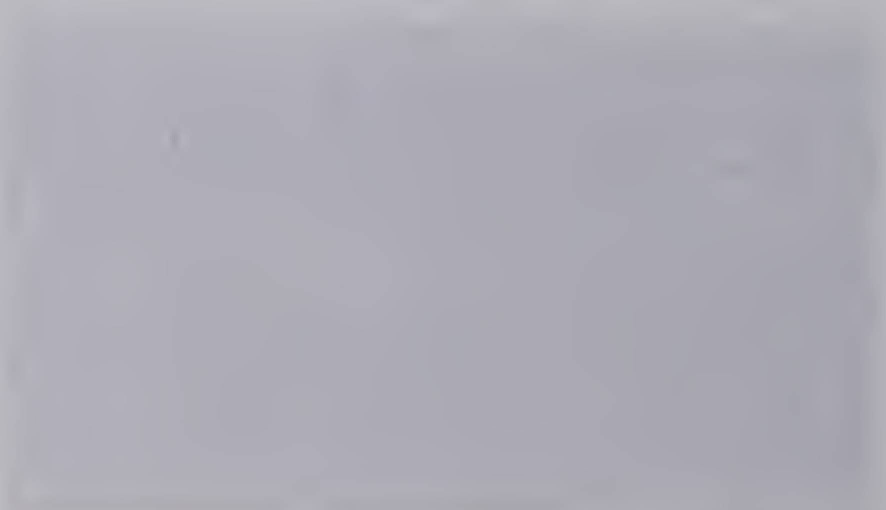


PLATE 14

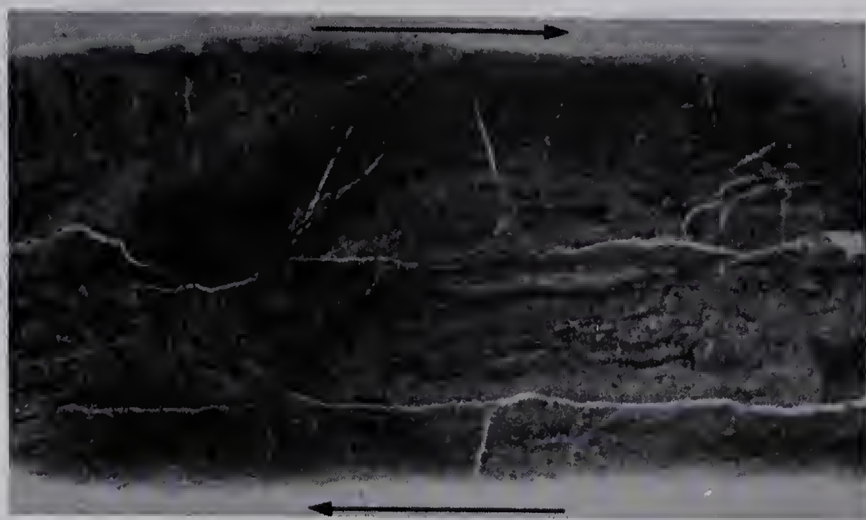


FIGURE 1. Type II cracking pattern
Sample SRW-39A

FIGURE 2. Type II cracking pattern
Sample SRW-39B

FIGURE 3. Type I and Type II cracking pattern
Sample P-54A

Sample DL-5, WDR = 11

Sample P-1, WDR = 13

Sample MRR-4, WDR = 17

Sample MP-2, WDR = 19

FIGURE 1. Wet-dry-cycle rating

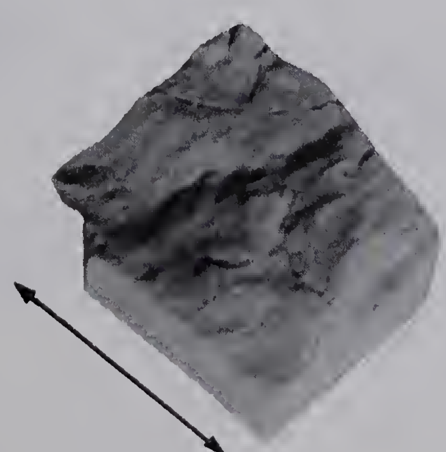


FIGURE 2. Irregular failure plane
Sample MRR-74A

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APPENDIX A

APPENDIX A

PREPARATION OF THIN SECTIONS

1. Impregnate sample with Canada balsam-xylene mixture or carbowax (as discussed in thesis).

2. Cut sample perpendicular to the bedding with hacksaw blade to obtain a slab about 1/8 inch in thickness.

3. Polish one side of the slab and mount it onto a glass slide. For samples impregnated with Canada balsam, use Canada balsam as a mounting cement. For samples impregnated with carbowax, use epoxy resin as a mounting cement since they must be "cold" mounted.

4. Grind the slab by a lap wheel and carbide grit; then polish with Tufbak Darite abrasive paper to a thickness of approximately 30 microns.

5. Cover the slide with a glass cover slip and use either Canada balsam-toluene mixture or resin as a mounting cement.